

**SEDIMENTOLOGY, ICHNOLOGY AND
SEQUENCE STRATIGRAPHY OF THE UPPER
DEVONIAN-LOWER CARBONIFEROUS
BAKKEN FORMATION IN THE SOUTHEASTERN
CORNER OF SASKATCHEWAN**

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Saskatoon

By

Liya Zhang

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ABSTRACT

The Upper Devonian-Lower Carboniferous Bakken Formation is present in the subsurface of the Williston Basin in northeastern Montana, North Dakota, southwestern Manitoba and southern Saskatchewan. In the southeastern corner of Saskatchewan, the Bakken Formation either conformably overlies the Upper Devonian Big Valley Formation or unconformably overlies the Torquay Formation, and is conformably overlain by the Lower Carboniferous Souris Valley (Lodgepole) Formation. The Bakken Formation typically includes three members: the lower and upper organic-rich black shale, and the middle calcareous/dolomitic sandstone and siltstone, which makes a “perfect” petroleum system including source rock, reservoir, and seal all within the same formation. According to detailed core analysis in the southeastern corner of Saskatchewan, the Bakken Formation is divided into eight facies, and one of which (Facies 2) is subdivided into two subfacies: Facies 1 (planar cross-stratified fine-grained sandstone); Facies 2A (wavy- to flaser-bedded very fine-grained sandstone); Facies 2B (thinly parallel-laminated very fine-grained sandstone and siltstone); Facies 3 (parallel-laminated very fine-grained sandstone and muddy siltstone); Facies 4 (sandy siltstone); Facies 5 (highly bioturbated interbedded very fine-grained sandstone and siltstone); Facies 6 (interbedded highly bioturbated sandy siltstone and micro-hummocky cross-stratified very fine-grained sandstone); Facies 7 (highly bioturbated siltstone); and Facies 8 (black shale). Our integrated sedimentologic and ichnologic study suggests that deposition of the Bakken occurred in two different paleoenvironmental settings: open marine (Facies 4 to 8) and brackish-water marginal marine (Facies 1 to 3). The open-marine facies association is characterized by the distal *Cruziana* Ichnofacies, whereas the brackish-water marginal-marine facies association is characterized by the depauperate *Cruziana* Ichnofacies. Isochore maps shows that both open-marine and marginal-marine deposits are widely distributed in this study area, also suggesting the existence of a N-S trending paleo-shoreline. The Bakken strata in this study area represent either one transgressive systems tract deposits or two transgressive systems tracts separated by a

coplanar surface or amalgamated sequence boundary and transgressive surface. This surface has been identified in previous studies west-southwest of our study area, therefore assisting in high-resolution correlation of Bakken strata.

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LIST OF ABBREVIATIONS

BI - bioturbation index

FSST - falling stage systems tract

HCS - hummocky cross-stratification

HST - highstand systems tract

Ne. - *Nereites missouriensis*

Pa. - *Palaeophycus tubularis*

Ph. - *Phycosiphon incertum*

Pl. - *Planolites montanus*

Ro. - *Rosselia* isp.

SB - sequence boundary

Te. - *Teichichnus rectus*

TOC - total organic carbon

TS - transgressive surface

TST - transgressive systems tract

1. INTRODUCTION

The Bakken Formation is not only a world-class light oil reservoir in the United States (North Dakota and Montana), but also a very important Canadian play. This formation is present in the subsurface of southern Saskatchewan and southwestern Manitoba in the Williston Basin, representing one of the largest light oil reservoirs discovered in Western Canada. The Bakken Formation represents a “perfect” hydrocarbon system, including source rock, reservoir, and seal all within the same formation (Halabura et al., 2007).

The Bakken reservoir was first discovered in the 1950’s, but because of its lower porosity and permeability, its vast petroleum reserves were only recently accessible by technics of drilling horizontal wells and multi-staged hydraulic fracture stimulation (Kreis et al., 2005; Kohlruess and Nickel, 2009). In Saskatchewan, it is estimated that there are 25 to 100 billion barrels of original oil in place within reservoirs of the Bakken Formation (Luo and Coulson, 2014).

A number of studies on the Bakken Formation in southeastern Saskatchewan have been published in recent years. In particular, Angulo and Buatois (2012a) did an integrated sedimentological and ichnological analysis, providing a more accurate picture of the depositional history of the Bakken Formation. The study area in this thesis research is just located to the east-northeast of the study area mentioned above, in the southeastern corner of Saskatchewan, from Townships 5 through 16, Ranges 30W1 to Range 2W2; the Rocanville oil field of the Bakken Formation and the Ryerson oil field of the Bakken and Torquay formations are located in this area (Figure 1).

This thesis research will help to document the sedimentary facies, trace fossils, depositional environment and sequence stratigraphy of the Bakken Formation in the southeastern corner of Saskatchewan, therefore allowing a better understanding of reservoir geometry and heterogeneity, and potential traps, assisting in oil exploration and production.

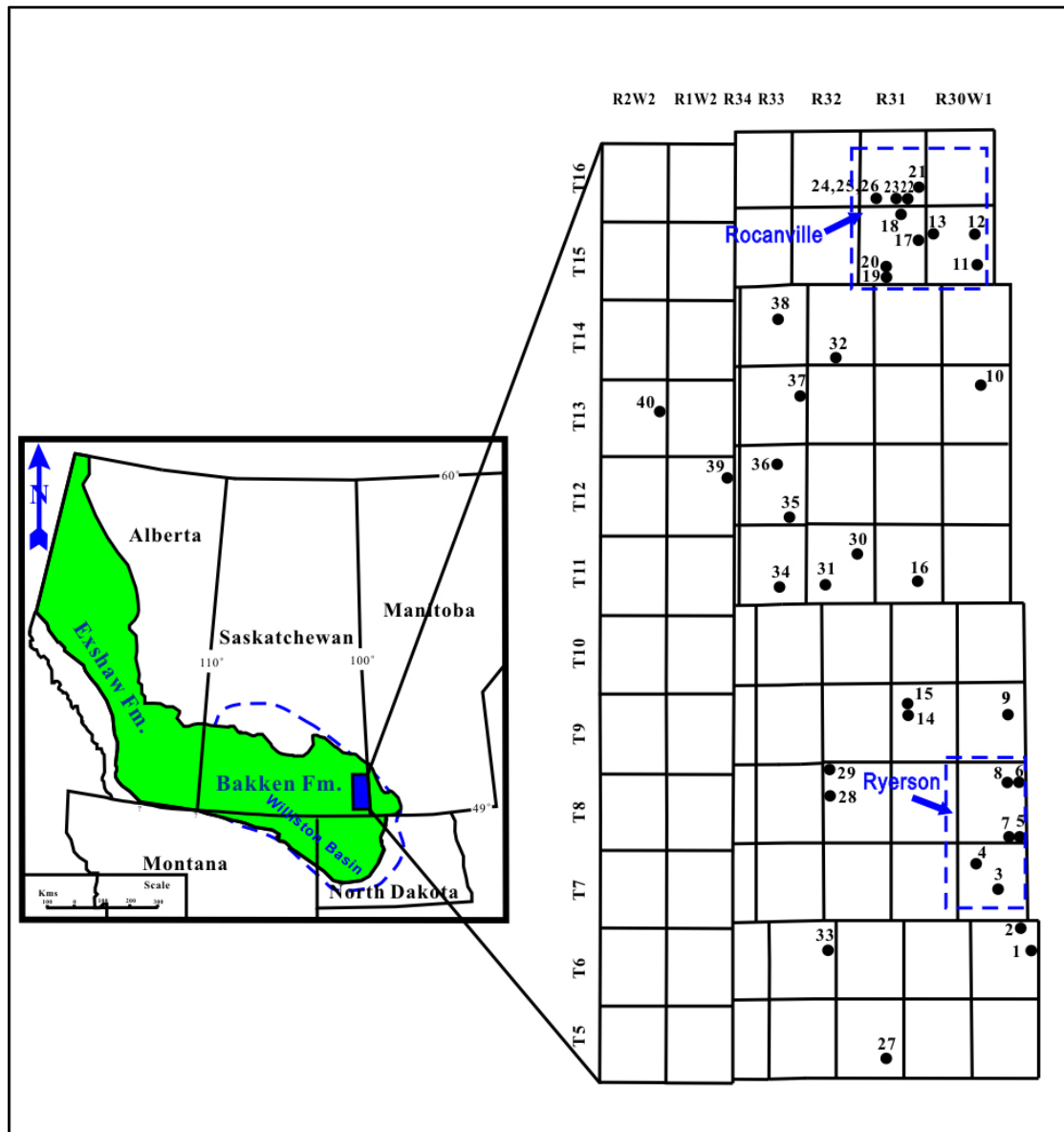


Figure 1- Left: area map showing in green the spatial distribution of the Bakken Formation and equivalent Exshaw Formation, and showing in blue this study area located in the southeastern corner of Saskatchewan. The blue dashed line shows the Williston Basin (after Smith et al., 1995; Angulo et al., 2008). Right: map of the study area showing well locations of the described Bakken cores. The blue dashed lines show two oil fields in this study area.

1.1. Research Objectives

The main goals of this thesis research are:

- (1) To provide a detailed, integrated sedimentologic, ichnologic, and sequence-stratigraphic analysis of the Bakken Formation in the southeastern corner of

Saskatchewan

(2) To compare the sedimentary facies and stratal architecture of the Bakken Formation in this area with those documented to the west-southwest by Angulo and Buatois (2012a), and to understand the differences of facies expression and sequence-stratigraphic evolution along a proximal-distal axis of the basin.

The specific objectives are:

- (1) To describe and interpret the sedimentary facies of the Bakken Formation based on core analysis
- (2) To identify facies associations in terms of depositional environments
- (3) To characterize trace fossils and ichnofacies
- (4) To construct isochore maps of each sedimentary facies and analyze facies distribution
- (5) To provide a sequence-stratigraphic framework of the Bakken Formation in this research area

1.2. Research Methods and Basic Concepts

The application of ichnology is being increasingly recognized as a powerful tool for paleoenvironmental reconstructions, because trace fossils can provide an *in situ* record of environment and environmental change, based on factors that influence benthic organisms (Ekdale et al., 1984; Bromley, 1996; MacEachern and Gingras, 2007; Buatois and Mángano, 2011). They can constrain important environmental variables, such as salinity, oxygen, and food supply, which are not commonly recorded in the original sedimentary fabric (Pemberton et al., 1992; Buatois and Mángano, 2011; Angulo and Buatois, 2012b). Therefore, the integration of ichnologic and sedimentologic datasets can provide a more accurate picture of depositional conditions, assisting in reservoir characterization (e.g. Buatois et al., 2007; Buatois et

al., 2013).

This project is mainly based on core descriptions and interpretations. Forty cores have been analyzed in detail. Figure 1 (right) shows well locations of described Bakken cores, and Table 1 shows the list of 40 wells logged in this study, where the well numbers are consistent with the well locations in Figure 1. All the cores examined have been slabbled in order to improve the recognition of sedimentologic and ichnologic features. Facies are defined based on sedimentary texture and structures, bed contacts, bioturbation index, and ichnofaunal composition.

Eight facies and two subfacies are identified in this research area. They are grouped into two depositional environments: the open-marine facies association and the marginal-marine embayment facies association. The open-marine environmental subdivision is based on Buatois and Mángano (2011), adapted from MacEachern et al. (1999a), in which the shelf is located below the storm-wave base, the offshore and offshore transition are located between the storm-wave base and the fair-weather wave base, and the shoreface is located between the fair-weather wave base and the low-tide line. The marginal-marine embayment environmental subdivision is based on MacEachern and Gingras (2007), in which restricted bays are defined as embayments that have limited or intermittent connection to the open sea, and are subdivided into distal-bay, bay-margin, and bay-mouth subenvironments.

Bioturbation reflects to the disruption or reworking of original sedimentary fabrics by the activity of organisms (Frey and Wheatcroft, 1989), and can be analyzed by the ichnofabric approach. The ichnofabric approach is usually based on observations in cross-sections, where cross-cutting relationships and tiering structures can be evaluated (Buatois and Mángano, 2011). The Bioturbation Index (BI) of Taylor and Goldring (1993), defined in terms of burrow density, amount of burrow overlap and the sharpness of the original sedimentary fabric, is used in this study. According to this scheme, BI = 0 (0%) is represented by no bioturbation; BI = 1 (1-4%) is characterized by sparse bioturbation with few discrete traces; BI = 2 (5-30%) is for low bioturbation in sediment that still has preserved sedimentary structures; BI = 3

Well Number	Well Identification	License Number	Core Interval(m)
1	131/12-24-006-30W1	05J209	1092.20-1098.70
2	131/15-35-006-30W1	07K132	1077.00-1095.00
3	121/15-15-007-30W1	06E187	1085.00-1096.00
4	111/09-29-007-30W1	06H495	1096.90-1114.00
5	141/14-01-008-30W1	06B107	1026.00-1036.70
6	101/09-25-008-30W1	06H319	993.00-1003.40
7	141/12-02-008-30W1	02G378	1038.40-1056.40
8	101/08-26-008-30W1	06I122	1015.00-1033.00
9	101/03-23-009-30W1	08A041	972.50-988.50
10	111/07-27-013-30W1	09L121	753.00-771.00
11	141/07-11-015-30W1	09J069	662.50-680.50
12	121/05-23-015-30W1	86B069	645.00-663.20
13	101/10-19-015-30W1	97C030	667.25-685.50
14	131/16-17-009-31W1	08J375	1067.50-1084.75
15	131/16-20-009-31W1	06H322	1069.00-1087.00
16	101/01-10-011-31W1	05I238	963.00-981.00
17	121/16-24-015-31W1	96F084	681.50-690.70
18	101/08-34-015-31W1	96E128	671.50-680.70
19	101/16-04-015-31W1	98B127	726.00-744.00
20	101/01-09-015-31W1	98I033	727.40-745.40
21	101/10-12-016-31W1	94L133	650.00-668.00
22	121/02-02-016-31W1	96F121	666.00-675.00
23	121/05-03-016-31W1	95A008	674.50-687.30
24	101/08-05-016-31W1	59C012	687.02-702.26
25	101/09-05-016-31W1	85J188	685.00-703.00
26	101/10-05-016-31W1	59L052	686.10-700.70
27	101/13-11-005-32W1	66E073	1325.27-1343.56
28	121/02-19-008-32W1	06H069	1218.00-1234.00
29	101/01-31-008-32W1	06H080	1201.50-1271.50
30	141/05-23-011-32W1	10F105	975.00-993.35
31	141/13-08-011-32W1	10D224	1019.00-1037.00
32	111/09-04-014-32W1	08I283	859.00-877.10
33	101/06-24-006-33W1	06I015	1326.00-1344.00
34	101/03-10-011-33W1	10H250	1091.50-1109.50
35	141/16-02-012-33W1	10F097	1007.00-1025.00
36	131/13-27-012-33W1	10F135	971.50-985.05
37	101/16-24-013-33W1	07L095	883.00-900.00
38	102/09-22-014-33W1	11A306	856.00-874.00
39	141/11-25-012-01W2	10F104	1048.00-1066.00
40	131/16-24-013-02W2	07H346	1034.00-1052.20

Table 1- List of 40 wells logged in this study. The well numbers are consistent with the well locations in Figure 1.

(31-60%) describes an ichnofabric with discrete trace fossils, moderate bioturbation and still distinguishable bedding boundaries; BI = 4 (61-90%) is suggested by intense bioturbation, high trace-fossil density, common overlap of trace fossils, and primary sedimentary structures are mostly erased; BI = 5 (91-99%) is indicated by sediment with completely disturbed bedding and intense bioturbation; BI = 6 (100%) is for completely bioturbated and reworked sediment.

Ichnofacies are conceptual constructs which involves the distillation process or selection of key features within a representative sample of discrete ichnocoenoses of a wide range of ages formed under a similar set of environmental conditions and the articulation of these key features, linking concepts and organizing them in a coherent structure (Buatois and Mángano, 2011). There are four main types of ichnofacies: softground marine ichnofacies, substrate-controlled ichnofacies, continental invertebrate ichnofacies, and vertebrate ichnofacies. Five ichnofacies have been identified within the first group, namely *Psilonichnus*, *Skolithos*, *Cruziana*, *Zoophycos*, and *Nereites*.

The *Cruziana* Ichnofacies has been further subdivided by MacEachern et al. (1999a, 2007), into archetypal *Cruziana* Ichnofacies; proximal *Cruziana* Ichnofacies, which is transitional with the *Skolithos* ichnofacies, and dominated by dwelling structures of suspension feeders and passive predators; and distal *Cruziana* Ichnofacies which is transitional with the *Zoophycos* Ichnofacies, and dominated by grazing trails and specialized feeding traces. When the *Cruziana* Ichnofacies occurs in protected areas of brackish-water marginal-marine settings, such as estuaries, deltas and bays, it tends to present a depauperate expression resulting from the stressful conditions; characterized by reduced abundance, diversity and size, and dominated by simple structures of trophic generalists (MacEachern and Pemberton, 1994).

The trace fossil assemblages of the open-marine facies association identified in this thesis research belong to the distal *Cruziana* Ichnofacies, and the trace fossil assemblages of the brackish-water marginal-marine facies association belong to the depauperate *Cruziana* Ichnofacies. The *Cruziana* Ichnofacies is characterized by (1)

dominance of horizontal traces and subordinated presence of vertical and inclined structures; (2) a variety of ethological groups, including locomotion, feeding, resting, dwelling structures, and grazing trails; (3) dominance of deposit and detritus feeding traces, with suspension feeding and predation also involved; (4) dominance of structures produced by a mobile fauna and subordinate presence of permanent dwelling structures; and (5) high ichnodiversity and high abundance (Figure 2) (Seilacher, 1964, 1967; Buatois and Mángano, 2011).

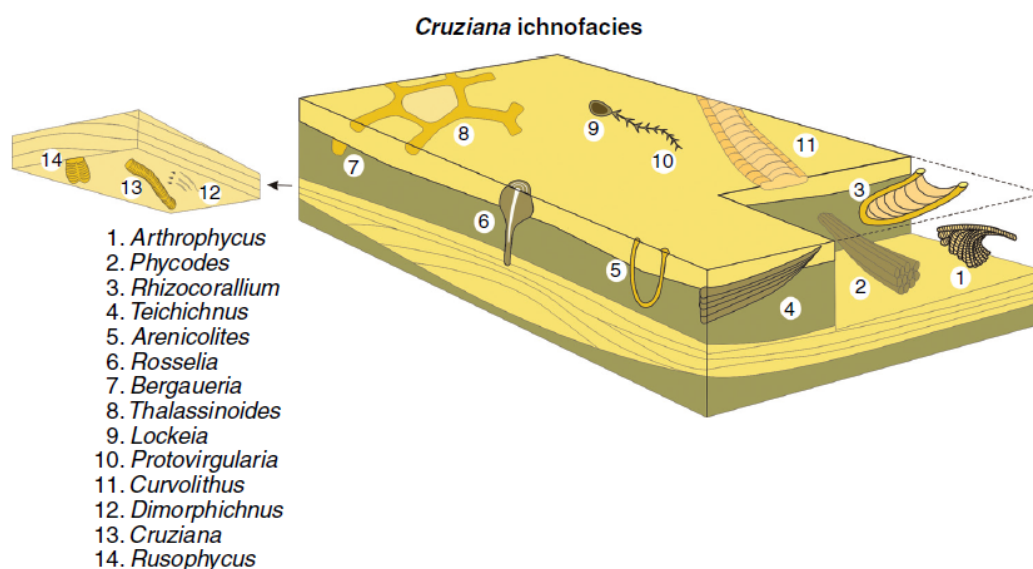


Figure 2- Characteristics of the *Cruziana* Ichnofacies model (after Buatois and Mángano, 2011).

Isochore maps are constructed for most of the facies or subfacies by software Surfer 12, either based on core thickness or well logs, to provide a better understanding of the sedimentary facies distribution. For the open-marine facies, except for the lower and upper shale members (Facies 8), no vertical reoccurrence is present in this study area; therefore, the isochore maps indicate discrete thickness. Due to the limited presence in this study area, no isochore map is constructed for the lower black shale, whereas an isochore map is made for the upper black shale which also reflects discrete thickness. For the brackish-water marginal-marine facies or subfacies, some of them reoccur vertically, therefore, the isochore maps reflects the

net thickness. For the upper shale member, the isochore maps are made from well logs, whereas for all the other facies, the isochore maps are based on core thickness. Most of the contacts between each facies or subfacies are gradational; therefore, the thickness measurement is approximate in some cases.

1.3. Description of the Bakken Formation

The Bakken Formation typically includes three members: the lower and upper organic-rich black shales, and the middle calcareous/dolomitic sandstone and siltstone. The three members of the Bakken Formation display an onlapping relationship, and converge and thin towards the margins of the Williston Basin (Smith et al., 1995), which indicates the upper member has the largest extension while lower member has smallest extension.

The lower Bakken member consists of massive to locally parallel-laminated, organic-rich black shale. In deeper portions of the basin, it is considered to be mature source rock (LeFever et al., 1991). The lower Bakken shale has an average TOC (total organic carbon) content of 8%, with a maximum of 20% (Smith and Bustin, 1997). The maximum thickness of the lower Bakken shale reaches 20 m near the basin depocenter in North Dakota (LeFever et al., 1991). The thickness in Saskatchewan generally ranges from 6 to 8 m (Christopher, 1961). Based on conodont biostratigraphy, the lower shale member has been assigned to the late Famennian (Late Devonian) (Hayes, 1985). Brachiopod, gastropod, cephalopod, bivalve, ostracode, arthropod remains and fish scales occur in the lower Bakken shale (Thrasher, 1985). Trace fossils are generally absent in the lower Bakken black shale, except for local *Chondrites* and *Thalassinoides* observed at the top of some cores, and *Zoophycos*, *Phycosiphon* and *Chondrites* observed in outcrops of the equivalent Exshaw Formation at Crowsnest Lake (Angulo et al., 2008; Angulo and Buatois, 2012b).

The middle Bakken member consists of calcareous/dolomitic sandstone and

siltstone, and displays a wide variety of lithofacies (Figure 3). Christopher (1961) defined units A and B, and the latter was further subdivided into 4 subunits, B1, B2, B3 and B4. LeFever et al. (1991) kept B1, B2, and B3 in unit B, but placed B4 in unit C. Subsequently, several other authors continued to use this nomenclature, but have come up with more detailed facies definition (e.g., Smith and Bustin, 1996; Angulo and Buatois, 2012a). For this study, we have adopted the nomenclature of LeFever et al. (1991).

The upper Bakken member also consists of massive to locally parallel-laminated, organic-rich black shale, which is very similar to the lower Bakken member. It has an average TOC content of 10%, with a maximum of 35% (Smith and Bustin, 1997). Compared to the lower Bakken shale, the upper Bakken shale contains more abundance of conodonts and chonetid brachiopods (Christopher, 1961; LeFever et al., 1991). The maximum thickness of the upper Bakken shale is 9 m in North Dakota (LeFever et al., 1991). The average thickness in Saskatchewan is 1.2 m, with a maximum of 4 m (LeFever et al., 1991). Based on conodonts, Karma (1991a) assigned a middle Kinderhookian age (Early Mississippian) to the upper Bakken shale.

1.4. Previous Research

The Bakken Formation in southeastern Saskatchewan has been intensely studied by many authors. Fuller (1956) and Christopher (1961) did the early comprehensive work about lithofacies, depositional model, stratigraphy, geological structure and isopachs; they also proposed that the lower and upper Bakken shale were deposited in a regressive swamp environment, whereas the middle member was deposited in a transgressive shallow-marine environment. However, the swamp interpretation was abandoned later, being replaced by a shallow-marine model for all the Bakken members. Von Osinski (1970) performed studies about the geology and production



	'Gamma Ray Sonic	Description	Christopher (1961)		Thrasher (1985) Karma and Parslow (1989)		LeFever et al. (1991)		Smith and Bustin (1996)		Angulo & Buatois (2012)	
			Units/Subunits		Units		Units/Subunits		Subunits	Facies	Facies	
		Upper Member							Mb	1		
		B	B4	3	C		C	SMm,SMh	3B, 11			
			B3	2	B	B3	B	Sw, SI	9, 10			
			B2			B2		Sf, St, Sr, Lo	6, 7, 8			
			B1			B1		Sw, SI	4, 5			
		SILTSTONE, massive, dense, mottled, dolomitic, argillaceous, gray green, fossiliferous, disseminated pyrite, slightly bioturbated.										
		PARALLEL INTERBEDS OF DARK GRAY SHALE AND BUFF SILTY SANDSTONE, moderate to low bioturbated, calcareous, disseminated pyrite, mud drapes.										
SANDSTONE, internally complex, wavy and flaser bedded silty sandstone current ripples cross laminated silty sandstone with mud drapes, massive trough and planar cross-bedded sandstone. Few brachiopods, disseminated pyrite, buff to green, calcareous, slight to no bioturbation. Interbedded oolitic limestone												
PARALLEL INTERBEDS OF DARK GRAY SHALE AND BUFF SILTY SANDSTONE, moderate to very strong bioturbation disrupting laminae, disseminated pyrite, fossiliferous.												
SILTSTONE, massive, dense, mottled, very calcareous, argillaceous, gray green, highly fossiliferous, random orientation of fossils, disseminated pyrite.												

Figure 3- Lithology column and stratigraphic subdivision of Bakken Formation (after LeFever et al., 1991; Angulo et al., 2008; Angulo and Buatois, 2012a). Note facies can only be identified in cores, but not in well logs.

history of the Bakken Formation in the Rocanville oil field. In addition to these studies, LeFever et al. (1991) did work on source rock and oil migration, production, and reservoir characteristics. Karma (1991b) conducted his thesis about geochemistry of the Bakken Formation in Saskatchewan. Smith et al. (1995), and Smith and Bustin (1996, 1997, 1998, 2000) performed a series of studies on the Bakken Formation, including analysis of lithofacies, paleoenvironment, sequence stratigraphy, regional sedimentology, and source rocks. They proposed a lowstand offshore-shoreface depositional model for the middle Bakken member, consisting of a transgressive systems tract followed by lowstand systems tract and a second transgressive systems tract (Figure 4). Kreis et al. (2005, 2006) also did work on the stratigraphy, isopachs, source rock, hydrocarbon potential, and production history on the Bakken Formation. Angulo et al. (2008) proposed a normal-regressive offshore-shoreface and estuary depositional model for the middle Bakken member, and they suggested that the Bakken Formation comprises a basal transgressive systems tract followed by a highstand systems tract and a subsequent transgressive systems tract, whose base is considered as a coplanar surface of sequence boundary and transgressive surface (Figure 4). This upper transgressive systems tract encompasses marginal-marine to open-marine environments. However, Kohlruss and Nickel (2009) proposed a highstand offshore followed by falling-stage shoreface and transgressive offshore deposits (Figure 4). The normal regression to transgressive marginal- and open-marine model was further explored by Angulo and Buatois (2012a), who provided a detailed discussion of all alternative sequence-stratigraphic and depositional scenarios for the Bakken Formation. In addition, sedimentary facies distribution and petrophysical characterization in this study area were also presented (Angulo and Buatois, 2010, 2011). Also, Angulo and Buatois (2012b) and Buatois et al. (2013) discussed the significance of the Bakken Formation ichnofauna from a paleoenvironmental perspective and in connection with the Late Devonian mass extinction, respectively.


Stratigraphic Subdivisions	Smith and Bustin (2000)		Angulo et al. (2008)		Kohlruss and Nickel (2009)		Angulo and Buatois (2012)					
	Depositional Settings	Sequence Stratigraphy	Depositional Settings	Sequence Stratigraphy	Depositional Settings	Sequence Stratigraphy	Depositional Settings	Sequence Stratigraphy	Facies			
	Upper Member		Distal Marine	TST	Shelf	—?—	?	—?—	Shelf	—?—	1	
	Middle Member	C	Offshore		Upper Offshore	TST	Offshore	TST	Upper Offshore	TST	11, 3B	
			B	B3	Shoreface				LST		Estuary	Shoreface
		B2		6, 7 8A/B/C,								
		B1		Lower Shoreface		HST	Offshore	HST		Lower Shoreface	5	
		A	Offshore Transition	Offshore Transition	4							
			Upper Offshore	Upper Offshore	3A							
		Lower Offshore	Lower Offshore	2								
		Lower Member		Distal Marine	TST	Shelf	—?— TST	Relatively Deep Marine	—?— TST	Shelf	—?— TST	1

Figure 4- Lithology column, stratigraphic subdivision, and different depositional setting and sequence stratigraphy subdivisions that have been suggested for the Bakken Formation (after Smith and Bustin, 2000; Angulo et al., 2008; Kohlruss and Nickel, 2009; Angulo and Buatois, 2012a).

In short, the most recent integrated sedimentologic, ichnologic and sequence-stratigraphic studies in southeastern Saskatchewan (Townships 1 through 11, Ranges 3 to 25W2), including the Viewfield and Roncott oil fields, suggested a model of a shelf to shoreface during normal regression followed by a transgressive brackish-water embayment to open-marine setting for the middle Bakken member (Angulo and Buatois, 2012a).

2. GEOLOGICAL BACKGROUND

The Williston Basin is an intracratonic basin located at the western edge of the Canadian Shield (Martiniuk and Barchyn, 1994). The Bakken Formation is present in the subsurface of the Williston Basin in northeastern Montana, North Dakota, southwestern Manitoba and southern Saskatchewan (Fuller, 1956; Christopher, 1961; LeFever et al., 1991; Kreis et al., 2006) (Figure 1). Deposition of the Bakken Formation took place during the Late Devonian and Early Carboniferous, as indicated by conodont biostratigraphy in both the United States (Hayes, 1985) and Canada (Karma, 1991a; Johnston and Meijer Drees, 1993). During the Late Devonian, a shallow epicontinental sea covered much of the North American craton (Figure 5). The Bakken Formation is deposited in the Williston basin, near a north-south trending shoreline.

In southeastern Saskatchewan, the Bakken Formation is conformably overlain by limestone of the Lower Carboniferous Souris Valley (Lodgepole) Formation (Christopher, 1961; LeFever et al., 1991; Smith and Bustin, 1995; Nickel, 2010) (Figure 6). In much of southeastern Saskatchewan, the Bakken Formation conformably overlies greenish grey shales of the Big Valley Formation (Kreis et al., 2006; Nickel, 2010). However, the present study area is interpreted to have been an uplifted region before deposition of the Bakken strata (Christopher 1961; Sandberg, 1964; Kreis et al., 2006) (Figure 7). Therefore, in a few cases of this study area, the Bakken Formation overlaps the Big Valley Formation which terminates along a depositional edge (Nickel, 2010) (Figure 8), and unconformably overlies interbedded weathered dolostones, dolarenites, dolomitic mudstones and minor anhydrites of the Upper Devonian Torquay Formation (Christopher, 1961; Kreis et al., 2006).

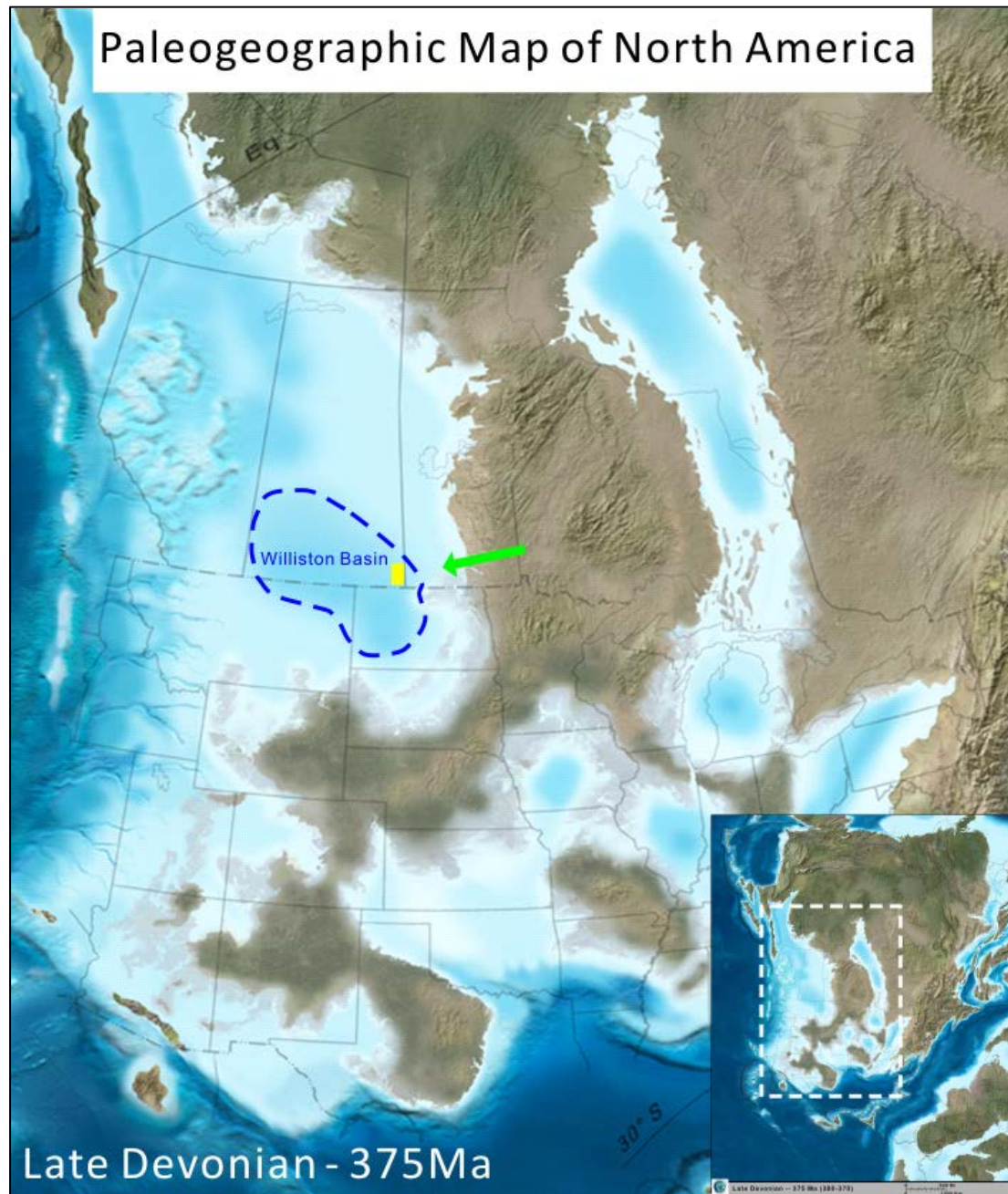


Figure 5- Paleogeographic map of North America in Late Devonian (375 Ma). The blue dashed line circles the location of the Williston Basin. The green arrow shows the potential sediment source from east-northeast direction. The study area is colored in yellow (after Blakey, 2013).


PERIOD		SOUTHEAST SASKATCHEWAN		
Carboniferous	Madison Group	Lodgepole	Souris Valley	
	Three Forks Group	Bakken Formation	Upper Bakken	
Middle Bakken				
Lower Bakken				
Big Valley				
Torquay				
Devonian	Saskatchewan Group	Birdbear		
		Duperow		

Figure 6- Stratigraphic chart showing subdivisions within the Devonian/Carboniferous Three Forks Group as well as the stratigraphy of overlying and underlying strata (after Nickel, 2010).

The total thickness of the Bakken Formation generally varies from 0 to 30 m, being only locally over 70 m as a result of salt collapse (Christopher, 1961; LeFever et al., 1991; Smith et al., 1995; Kreis et al., 2006). In the southeastern corner of Saskatchewan, beyond the eastern extent of lower Bakken shale (Figure 7, Figure 8), the Bakken Formation only consists of the upper black shale and middle sandy to silty member, which unconformably overlies the Torquay Formation (Christopher, 1961; Von Osinski, 1970; Kreis et al., 2006).

In Alberta and British Columbia, the lower black shale and middle sandy to silty member are equivalents of the Exshaw Formation, whereas the upper black shale member correlates with the Banff Formation (Christopher, 1961; Smith et al., 1995).

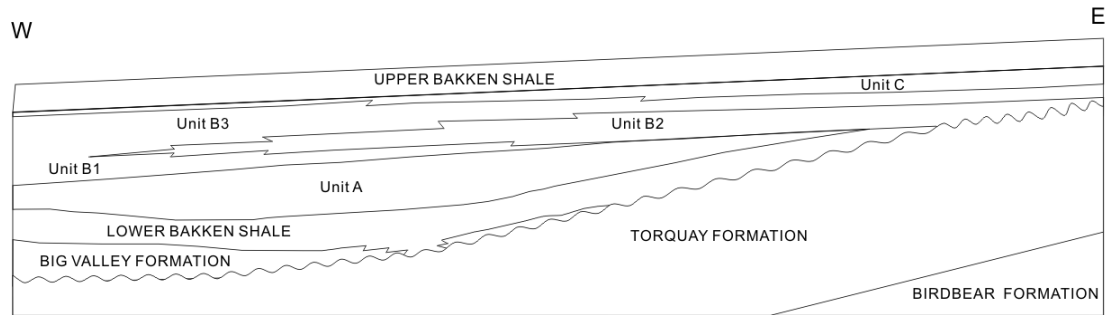


Figure 7- Stratigraphic cross section showing the relationship of the Bakken Formation (lower and upper black shale, Unit A, B and C of the middle member), the Big Valley Formation and the Torquay Formation (modified from Christopher, 1961).

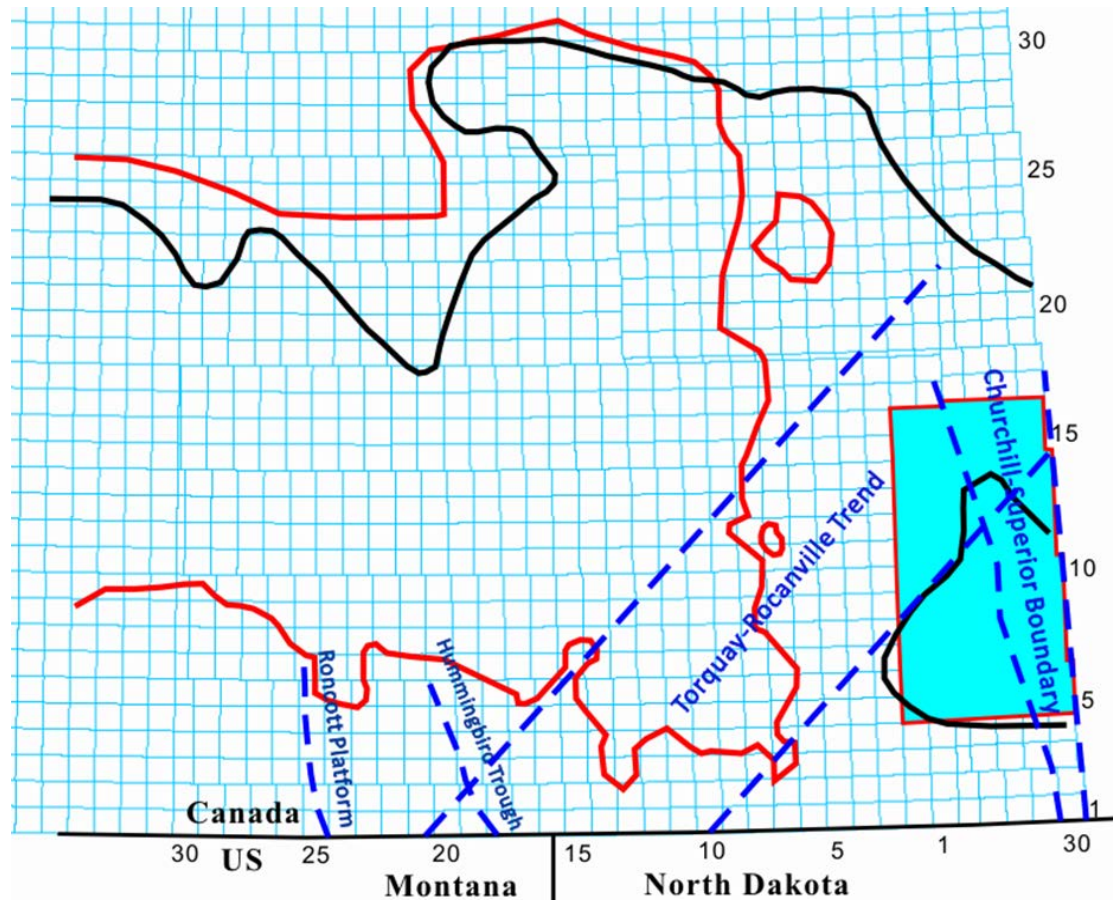


Figure 8- Map of southeastern Saskatchewan with townships, showing the study area (blue) in the southeastern corner of Saskatchewan. The red line shows the zero edge of the Big Valley Formation, the black line shows the zero of the lower Bakken shale, and the blue dashed lines show main structural elements (modified from Kreis et al., 2006; Kohlruss and Nickel, 2009).

3. SEDIMENTARY FACIES

Based on detailed core analysis in this study area, the Bakken Formation is divided into eight facies, and one of which (Facies 2) is subdivided into two subfacies: Facies 1 (planar cross-stratified fine-grained sandstone); Facies 2A (wavy- to flaser-bedded very fine-grained sandstone); Facies 2B (thinly parallel-laminated very fine-grained sandstone and siltstone); Facies 3 (parallel-laminated very fine-grained sandstone and muddy siltstone); Facies 4 (sandy siltstone); Facies 5 (highly bioturbated interbedded very fine-grained sandstone and siltstone); Facies 6 (interbedded highly bioturbated sandy siltstone and micro-hummocky cross-stratified very fine-grained sandstone); Facies 7 (highly bioturbated siltstone); and Facies 8 (black shale).

A general comparison of facies identified in this study (relatively proximal location) with those described by Angulo and Buatois (2012a) (relatively distal location) is provided in Table 2. Compared with the facies identified in southeastern Saskatchewan, in addition to the upper-offshore deposits, we also identify lower-offshore and offshore-transition deposits in unit C of the middle member in the southeastern corner of Saskatchewan; Subunits B2 and B3 are also considered to be deposited in a brackish-water embayment in this study area; unit A and Subunit B1 of the middle member are not preserved in any of the cores logged in this study area. Less variety of facies has been identified in the southeastern corner of Saskatchewan, accordingly Facies 3A, 5, 7, 8B and 8C of Angulo and Buatois (2012a) are not present.

The following sections provide detailed descriptions and interpretations of these facies.

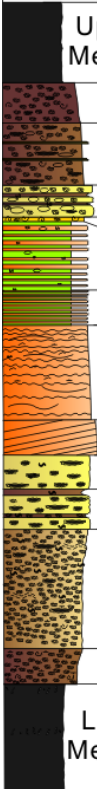
Stratigraphic Subdivision			Angulo and Buatois(2012) Southeastern of Saskatchewan	This Thesis Southeastern Corner of Saskatchewan	
			Facies and Environment	Facies	Environment
	Upper Member	Unit	1(Shelf)	8	Shelf
	C		2(Lower Offshore)	7	Lower Offshore
			3B(Upper Offshore)	6	Upper Offshore
				5	Offshore Transition
			11(Transgressive Lag)	4	Transgressive Lag
	B3		10(Distal Bay)	3	Distal Bay
			9(Bay Margin)	2B	Bay Margin
	B2		7(Wave-dominated Tidal Flat) 8A(Bay Margin) 8B(Distal Bay) 8C(Tidal Flat)	2A	
			6(Barrier Bar)	1	Barrier Bar
	B1		5(Lower Shoreface)		
			4(Offshore Transition)		
	A		3A(Upper Offshore)		
			2(Lower Offshore)		
	Lower Member		1(Shelf)	8	Shelf

Table 2- Comparison between facies identified in this study area in the southeastern corner of Saskatchewan (Townships 5 through 16, Ranges 30W1 to Range 2W2) and those from southeastern Saskatchewan (Townships 1 through 11, Ranges 3 to 25W2).

3.1 Facies 1: Planar Cross-stratified Fine-grained Sandstone Facies

(Figure 9a-b)

3.1.1 Description

This facies is composed of light grey, erosional-based, planar cross-stratified fine-grained sandstone. The bed thickness of cross-stratified sandstone ranges from 4 to 8 cm. Low-angle planar cross-stratification/parallel lamination, mudstone rip-up clasts, and some massive intervals are locally present. Bioturbation is absent. The description of Facies 1 is compromised by the limited database, since it occurs only in three of the cores logged in this study area. Facies 1 is generally present at the base of marginal-marine interval, albeit intercalated with Facies 2A in some cases.

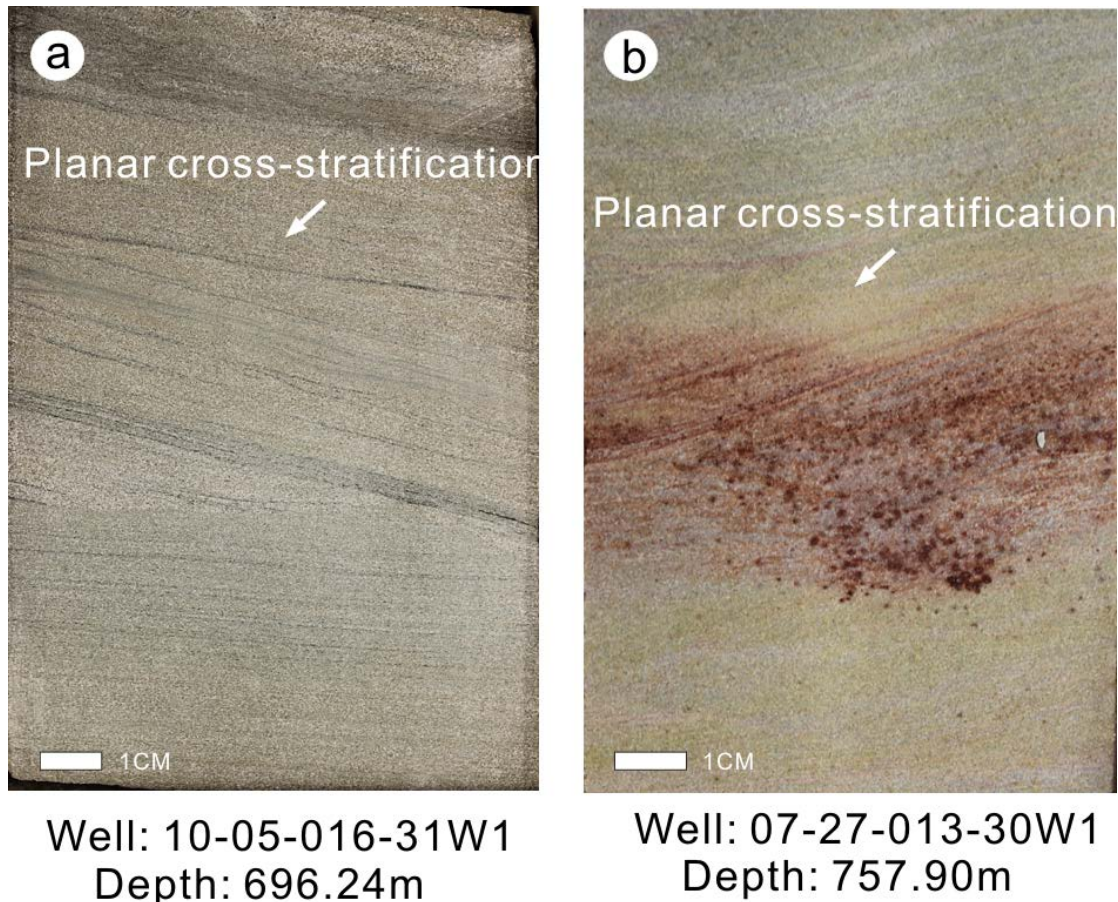


Figure 9- Core photos of Facies 1: Planar cross-stratified sandstone. (a) Note planar cross-stratification and low-angle planar cross-stratification/parallel lamination. (b) Close-up of planar cross-stratification. The red parts are oxidized.

3.1.2 Interpretation

Facies 1 represents deposition in a high-energy environment characterized by the dominance of planar cross-stratification and erosional base, which is produced by migration of two-dimensional dunes. The absence of bioturbation is attributed to double influence of both high-energy and stressful brackish-water conditions. Facies 1 is most likely deposited in a barrier bar located in the bay mouth (MacEachern and Gingras, 2007; Angulo and Buatois, 2012a). The localized occurrence/preservation of the barrier bar in this study area indicates the early-stage barrier-bar deposits are probably cannibalized by subsequent transgression (Cattaneo and Steel, 2003).

The typical modern analogues for Facies 1 are the barrier islands of west-central

Florida, such as the North Bunces Key and the Anclothe Key, which are typically wave-dominated, but also with tidal influence in the form of flood-tidal sand bodies (Davis et al., 2003). The dunes of North Bunces Key consist of well- to very well-sorted fine-grained sands, with uncommon mud and shell material, but common heavy minerals (Crowe, 1983). The dunes of Anclothe Key are mainly composed of homogeneous, well-sorted fine-grained sands, with prominent cross-stratification which is locally concentrated with phosphatic heavy minerals (Davis and Kuhn, 1985).

3.2 Facies 2A: Wavy- to Flaser-bedded Very Fine-grained Sandstone Facies (Figure 10a-d)

3.2.1 Description

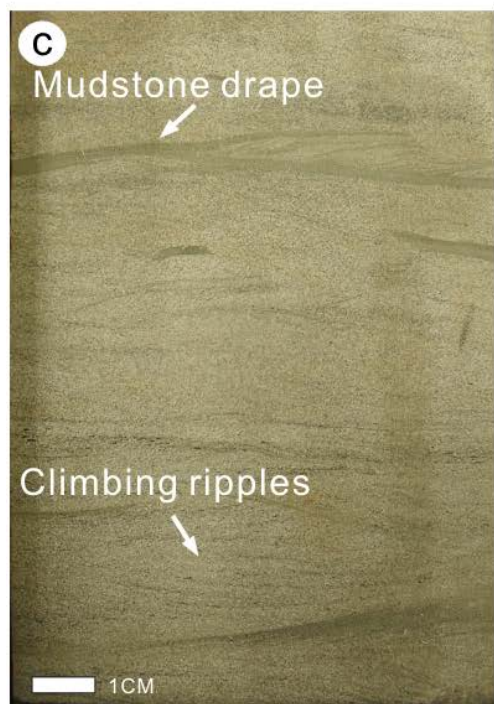
This facies is composed of light grey, wavy- to flaser-bedded very fine-grained sandstone. The bed thickness varies from less than 1 cm to tens of centimeters. Mudstone drapes, wave and current ripples (length ranges from 1.5 to 10 cm, amplitude varies from 0.5 to 1.5cm), and ripple cross-lamination are present. Climbing ripples are also locally present. Pyrite is common in this facies. Bioturbation is absent to very sparse, with only sporadic *Planolites montanus* confined to muddy parts. In the Rocanville area (northern part of the study area) (Figure 1), calcite-cemented blebs appear in some cores. Oil staining can be present, where there are no calcite blebs. The interval thickness of this facies varies from 0.15 to 6.5 m. The bed thickness of Facies 2A decreases upwards, passing into parallel lamination and grading into Facies 2B in most cases. However, Facies 2A can also be interstratified with Facies 1. In a few areas, Facies 2A unconformably overlies the Torquay Formation.



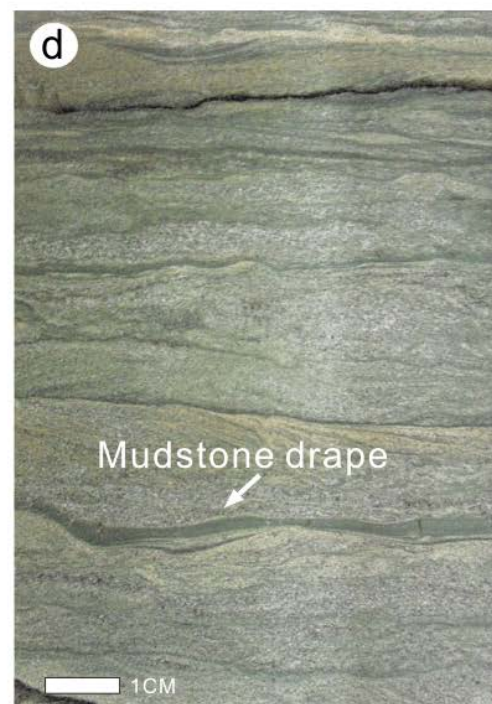
Well: 16-24-015-31W1
Depth: 683.69m



Well: 08-34-015-31W1
Depth: 679.19m



Well: 09-05-016-31W1
Depth: 696.29m



Well: 06-24-006-33W1
Depth: 1034.35m

Figure 10- Core photos of Facies 2A: Wavy-to flaser-bedded sandstone. (a) Ripple cross-lamination and pyrite. (b) Note the white calcite-cemented blebs, and the yellow parts are oil-staining. (c) Close-up showing mudstone drapes and climbing ripples. (d) Close-up showing mudstone drapes. The white parts are calcite-cemented.

3.2.2 Interpretation

Facies 2A was deposited in a setting characterized by relatively lower energy compared to Facies 1. The presence of mudstone drapes indicates tidal influence (Nio and Yang, 1991; Dalrymple, 2010). The ripple cross-lamination was formed when deposition took place during migration of current or wave ripples. Occasionally, high rate of deposition from probably decelerating flows is suggested by the local presence of climbing ripples (Walker and James, 1992). The low bioturbation index and the presence of monospecific suites of *Planolites* suggest stressful conditions for animal colonization. Facies 2A represents tidal-influenced sedimentation in a brackish-water environment, most likely a bay margin (MacEachern and Gingras, 2007; Angulo and Buatois, 2012a). The intercalation of Facies 2A and 1 reflects the interfingering of barrier-bar and bay-margin deposits, indicating the bay-margin deposits of Facies 2 are probably located around the back of barrier bar. The presence of only calcite blebs instead of pervasive calcite cement suggests that insufficient calcium remained within the formation waters when it reached the Rocanville area to fully fill pore spaces (Kohlruss and Nickel, 2009).

3.3 Facies 2B: Thinly Parallel-laminated Very Fine-grained

Sandstone and Siltstone Facies (Figure 11a-b)

3.3.1 Description

This facies is composed of medium to dark grey, thinly parallel-laminated very fine-grained sandstone and siltstone. Wavy lamination, current ripples (less than 2 cm in length) and mudstone drapes are present in some cases. Pyrite is also locally present. The bioturbation index is 0 to 1, and *Planolites montanus* is the only trace fossil identified, typically displaying small size. The interval thickness of Facies 2B is up to 2.4 m, and it tends to become sandier downwards, passing into Facies 2A gradationally, or unconformably overlying the truncated Torquay Formation.

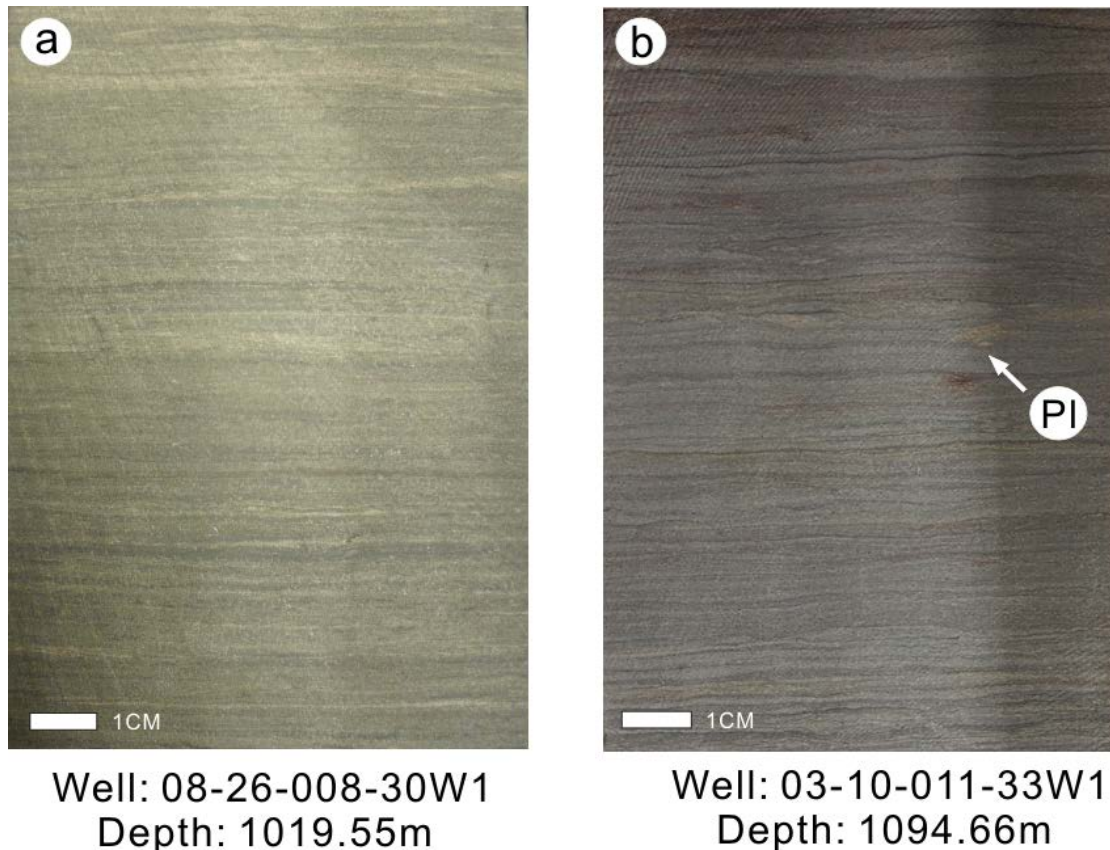


Figure 11- Core photos of Facies 2B: Thinly parallel-laminated sandstone and siltstone. (a) Note the pristine preservation of the primary fabric in the general absence of bioturbation. (b) General view of the facies showing monospecific suites of *Planolites montanus* (Pl).

3.3.2 Interpretation

The regular alternation of sandstone and siltstone, and presence of mudstone drapes suggest tidal influence during deposition (Nio and Yang, 1991; Dalrymple, 2010). Absence of storm deposits probably reflects a restricted setting protected from the open-marine waves. The low bioturbation index and the monospecific *Planolites* suite result from the stressful condition of marginal-marine settings which typically experience rapid fluctuations in environmental parameters, most likely reflecting brackish-water conditions (Gingras et al., 1999; MacEachern and Gingras, 2007). Facies 2B represents tidal-influenced sedimentation in a brackish-water environment, probably a bay margin near the mouth of fluvial systems (MacEachern and Gingras, 2007; Angulo and Buatois, 2012a).

The bay-margin deposits of Facies 2A and 2B resemble the marginal-marine deposits of the embayment complex recorded in the Viking Formation, Alberta (MacEachern et al., 1998, 1999b). Although the Viking Formation is also weakly bioturbated, it displays sporadically distributed trace fossils, such as *Planolites*, *Teichichnus*, *Terebellina*, *Palaeophycus*, *Lockeia*, *Skolithos*, and *Thalassinoides*. However, in this case of the Bakken Formation, the bay-margin deposits are rarely bioturbated, with *Planolites* being the only trace fossil present. This probably indicates the deposits were formed in a more restricted and stressful environment than the Viking Formation, most likely reflecting extreme brackish-water conditions.

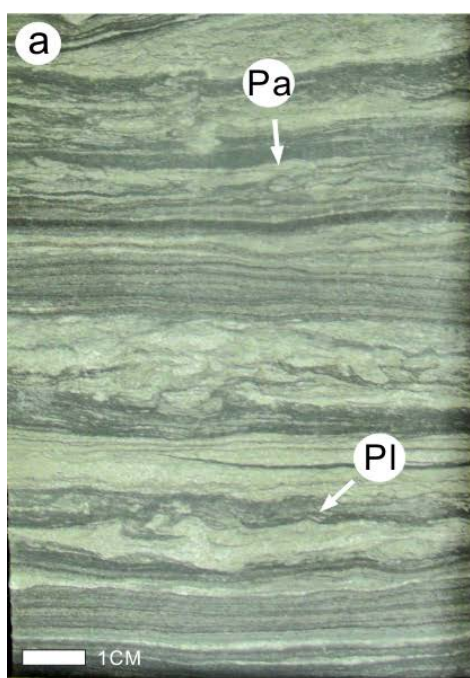
3.4 Facies 3: Parallel-laminated Very Fine-grained Sandstone and Muddy Siltstone Facies (Figure 12a-d)

3.4.1 Description

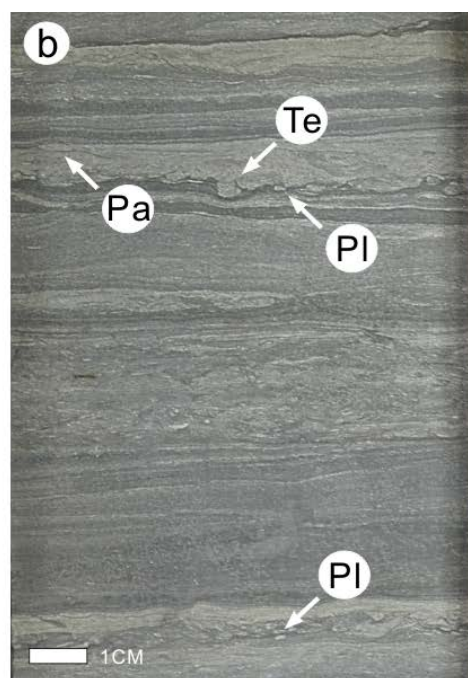
This facies is composed of parallel-laminated to locally parallel-bedded (about 2 cm in thickness) light grey, very fine-grained sandstone and dark grey muddy siltstone. Syneresis cracks are present. Thinly dark laminae of organic debris, soft-sediment deformation structures (micro-fault, convolute bedding and load structure), and 1 to 5 cm thick sharp-based laminated sandstone beds locally occur. The bioturbation index is 2 to 3; the dominant ichnotaxa are *Planolites montanus* and *Palaeophycus tubularis*, and the subordinate ones are *Rosselia* isp. and *Teichichnus rectus*. Facies 3 becomes less bioturbated downwards, passing gradationally into Facies 2B in most cases. The interval thickness of Facies 3 varies from 0.2 to almost 5 m.

3.4.2 Interpretation

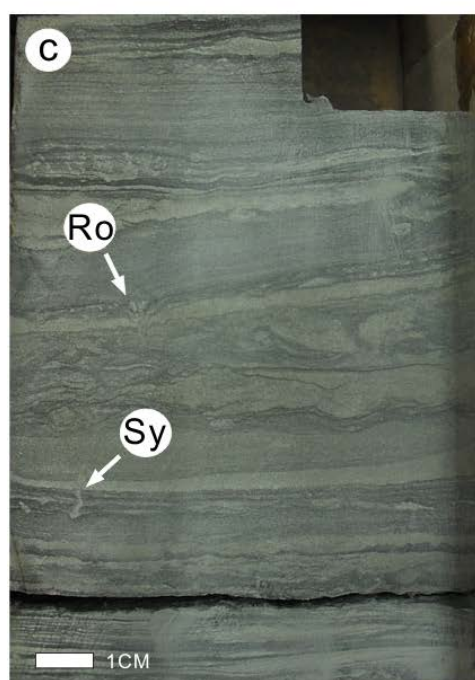
Facies 3 represents deposition in a generally low-energy environment. The interlamination of muddy siltstone and sandstone represents tidal rhythmites, which are small-scale sedimentary features, expressing deposition influenced by neap-spring and other tidal cycles (Archer, 1991; Archer, 1996; Kvale, 2003). The presence of



Well: 06-24-006-33W1
Depth: 1329.13m



Well: 01-09-015-31W1
Depth: 736.50m



Well: 01-10-011-31W1
Depth: 966.83m



Well: 07-27-013-30W1
Depth: 755.63m

Figure 12- Core photos of Facies 3: Parallel-laminated sandstone and muddy siltstone. (a) General view of the facies showing *Palaeophycus tubularis* (Pa) in sandstone and *Planolites montanus* (Pl) in muddy siltstone. (b) General view of the facies showing *Palaeophycus tubularis* (Pa), *Planolites montanus* (Pl) and *Teichichnus rectus* (Te). (c) Note syneresis crack (Sy), which suggests salinity fluctuations; and probably ichnofauna of *Rosselia* isp. (d) Close-up showing syneresis crack (Sy) and micro-faults.

syneresis cracks indicates salinity fluctuations in restricted conditions resulting in the shrinkage of sediment (Burst, 1965). The local presence of sharp-based laminated sandstone beds is explained as event beds and suggests sporadic storm activity. Trace fossils can be locally identified in the storm sandstone, probably escape trace fossils, resulting from animals trying to escape from burial during storms (Savrda and Nanson, 2003). The relatively higher bioturbation index and the increase in ichnodiversity compared to Facies 2 probably reflect less stressful conditions. However, they are mostly simple structures generated by trophic generalists (e.g., *Planolites*, *Teichichnus*), suggesting the environment is still stressful compared to the open-marine (Buatois and Mángano, 2011). Facies 3 is also considered to be deposited in a tidal-influenced brackish-water environment, most likely a distal bay relatively far from the area of fluvial discharge (MacEachern and Gingras, 2007; Angulo and Buatois, 2012a).

The distal bay deposits of Facies 3 are similar to the quiescent bay (central basin) deposits of the brackish-water estuary environment recognized by Hubbard et al. (2004) in the Cretaceous Bluesky Formation, Alberta, which also consist of interlaminated sandstone and muddy siltstone with moderate bioturbation and low ichnodiversity. The ichnofauna in those quiescent bay deposits of the Bluesky Formation consist of simple trace fossils, but in addition to *Planolites*, *Palaeophycus* and *Teichichnus*, trace fossils of *Cylindrichnus*, *Gyrolithes*, and *Thalassinoides* are also present.

3.5 Facies 4: Sandy Siltstone Facies (Figure 13a-b)

3.5.1 Description

This facies is composed of dark yellowish green, massive, granule- and pebble-bearing sandy siltstone, with mudstone rip-up clasts. Shell fragments are commonly present. Bioturbation index is 1 to 2. The ichnofauna consist of

Phycosiphon incertum and *Chondrites* isp. The interval thickness of Facies 4 is generally less than 10 cm. Where it occurs, it erosionally overlies brackish-water marginal-marine deposits, and gradationally passes into overlying open-marine offshore deposits. Facies 4 commonly occurs in southeastern to eastern part of the study area.

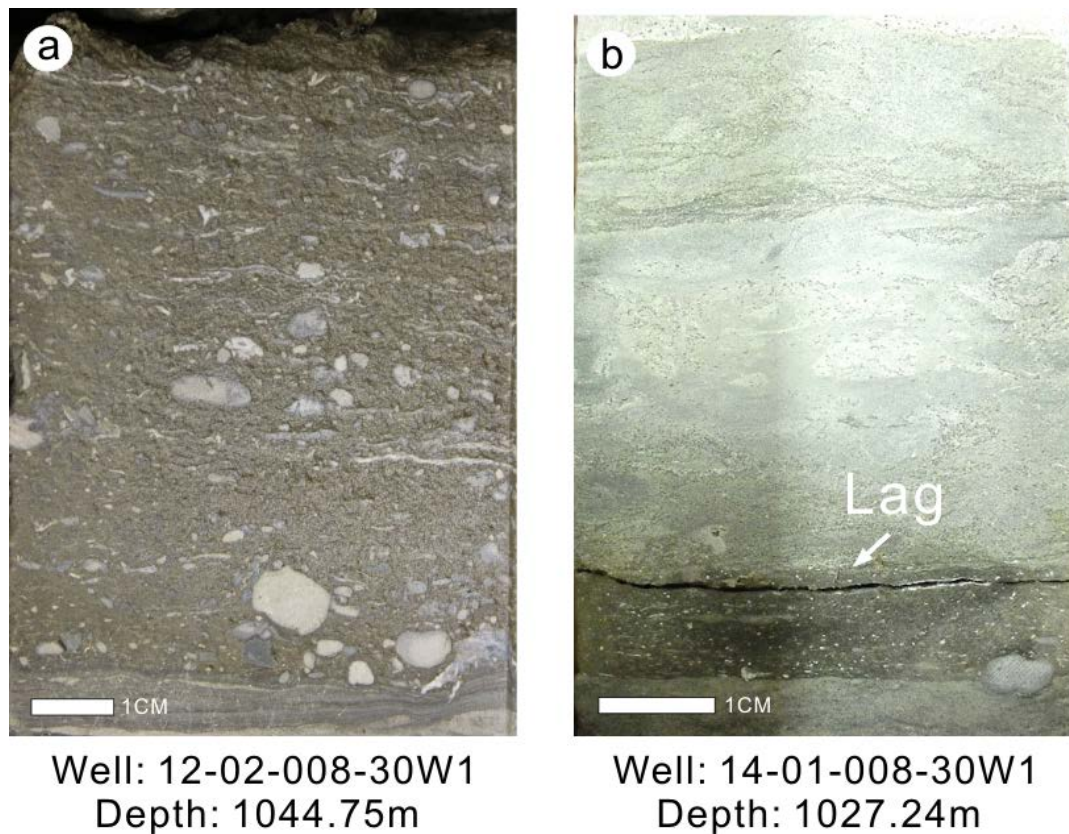


Figure 13- Core photos of Facies 4: Sandy siltstone. (a) Close-up showing abundant shell fragments. (b) General view of the transgressive lag with erosional base.

3.5.2 Interpretation

Facies 4 represents a transgressive lag produced due to high-energy ravinement in a basinwide transgression, during which time the shoreline moves towards the land, accompanied by a reduced sediment influx into the basin and erosion of the previously deposited sediments (Cattaneo and Steel, 2003). The contact between Facies 4 and underlying brackish-water marginal-marine deposits is an erosional surface. This surface may be regarded as an analogue of the wave-ravinement surface

of estuarine systems, reflecting erosion of the underlying brackish-water marginal-marine deposits, albeit in a bay setting (Zaitlin et al., 1994). The wave ravinement surface is an erosional surface, above which there is a fining-upward marine interval; a transgressive lag may or may not be present on top of the wave ravinement surface (Cattaneo and Steel, 2003).

3.6 Facies 5: Highly Bioturbated Interbedded Very Fine-grained Sandstone and Siltstone Facies (Figure 14a-d)

3.6.1 Description

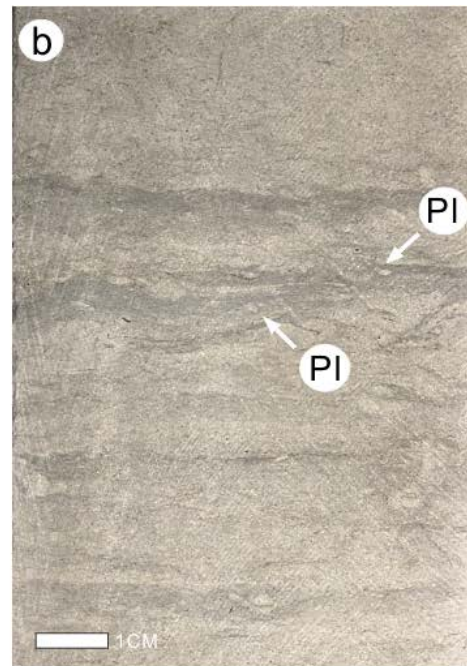
This facies is composed of highly bioturbated interbedded, light grey, massive, 1-15 cm thick, very fine-grained sandstone and thin layers (< 1cm) of siltstone. Micro-hummocky cross-stratified beds are present, albeit vary rarely. Most sandy tempestites are homogenized or only represented by some remnant lamination due to intensely biogenic reworking. The bioturbation index is 4 to 5, and displays burrowing uniformity; the dominant trace fossils are *Nereites missouriensis*, *Palaeophycus tubularis* and *Planolites montanus*, and subordinate ones are *Asterosoma* isp. and *Phycosiphon incertum*. The interval thickness of Facies 5 varies from 0.2 to 0.75 m. This facies passes gradationally upwards into Facies 6.

3.6.2 Interpretation

The thin layers of siltstone are interpreted as being deposited from suspension fallout during short periods of negligible wave action. The rarity of discrete sandstone beds with storm wave-generated structures most likely indicates that the storm beds are not thick enough to be preserved from the intense bioturbation. The burrowing uniformity indicates enough time available for colonization, and suites from both sandstone and siltstone crosscut each other, getting a mixed-up (MacEachern et al., 2010). It also suggests that the surrounding environment is quite hospitable for animals to colonize, probably with enough oxygen and food supply and no other



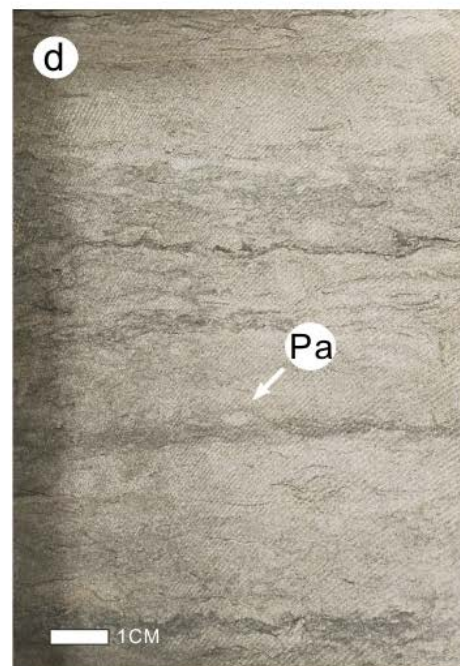
Well: 05-23-011-32W1
Depth: 983.73m



Well: 16-24-013-33W1
Depth: 891.76m



Well: 01-09-015-31W1
Depth: 733.77m



Well: 16-24-013-02W2
Depth: 1043.53m

Figure 14- Core photos of Facies 5: Interbedded highly bioturbated sandstone and thin layers of siltstone. (a) General view of the facies showing *Nereites missouriensis* (Ne) and *Palaeophycus tubularis* (Pa). The bed boundaries are not clear, due to intense bioturbation. (b) Note *Planolites montanus* (Pl) in the siltstone. (c) General view of the facies showing *Nereites missouriensis* (Ne) and *Planolites montanus* (Pl). (d) General view of the facies showing *Palaeophycus tubularis* (Pa).

significant environmental stresses. Thin siltstone layers from fair-weather deposition intercalated with a higher portion of sandstone beds from storm deposition suggesting deposition in a setting just below the fair-weather wave base, and therefore, Facies 5 is interpreted as deposited in an offshore-transition environment.

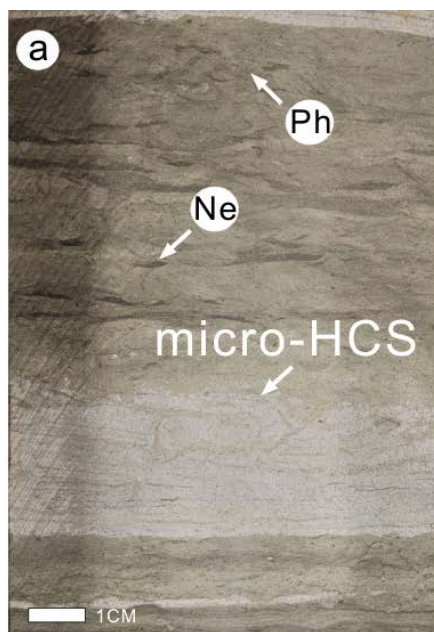
3.7 Facies 6: Interbedded Highly Bioturbated Sandy Siltstone and Micro-hummocky Cross-stratified Very Fine-grained Sandstone Facies (Figure 15a-d)

3.7.1 Description

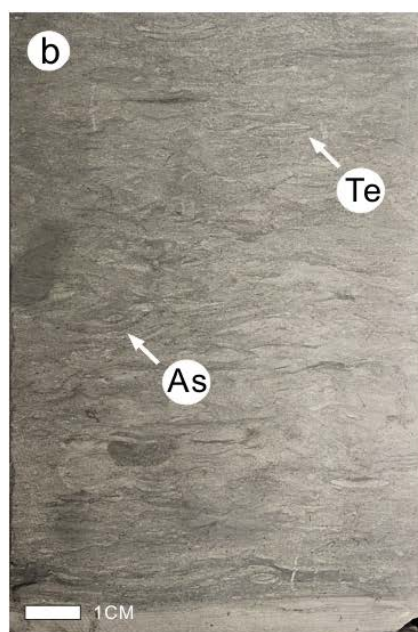
This facies is composed of interbedded medium to dark grey, highly bioturbated sandy siltstone to local silty sandstone and light grey, sparsely bioturbated micro-hummocky cross-stratified (micro-HCS) very fine-grained sandstone. The thickness of bioturbated sandy siltstone to silty sandstone varies from 6 to tens of centimeters, and shell fragments are locally present. The bioturbation index is 4 to 5; the dominant trace fossils are *Phycosiphon incertum* and *Nereites missouriensis*, subordinate ones are *Asterosoma* isp., *Teichichnus rectus*, *Planolites montanus*, and *Palaeophycus tubularis*. The thickness of micro-HCS sandstone beds varies from 1 to 5 cm, and those beds are sharp-based, and gradationally pass upwards into the highly bioturbated beds. Wave and combined-flow ripples are locally present on the top. The bioturbation index of these sandy deposits is 0 to 1, with only possible examples of *Conichnus* (dwelling or resting structure of sea anemones) having been recognized. In some cases, concentration of *Chondrites* isp. is present near the top of micro-HCS sandstone. The interval thickness of Facies 6 is up to 1.9 m, and it usually grades upwards into Facies 7.

3.7.2 Interpretation

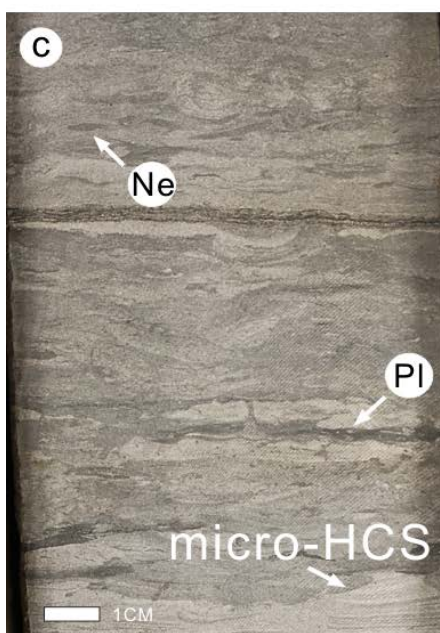
Facies 6 represents deposition in a setting characterized by the alternation of sedimentation from suspension fallout during fair-weather conditions and sand



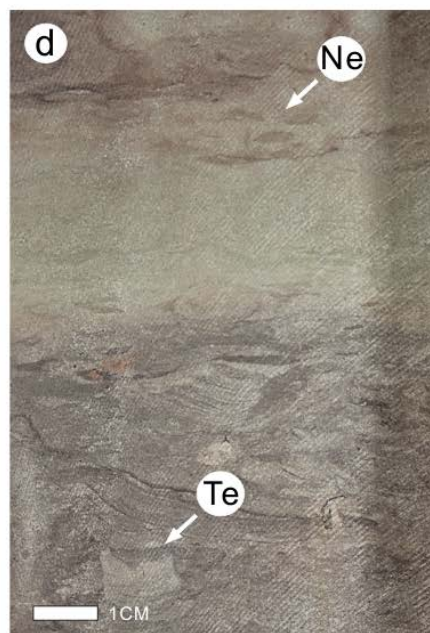
Well: 10-12-016-31W1
Depth: 654.41m



Well: 01-09-015-31W1
Depth: 732.31m



Well: 16-24-013-02W2
Depth: 1042.57m



Well: 03-10-011-33W1
Depth: 1093.39m

Figure 15- Core photos of Facies 6: Interbedded highly bioturbated sandy siltstone and micro-hummocky cross-stratified sandstone. (a) Close-up showing micro-hummocky cross-stratification (micro-HCS), and ichnofauna of *Phycosiphon incertum* (Ph) and *Nereites missouriensis* (Ne). (b) General view of the facies showing *Asterosoma* isp. (As) and *Teichichnus rectus* (Te). (c) Note micro-hummocky cross-stratification (micro-HCS), and the presence of *Planolites montanus* (PI) and *Nereites missouriensis* (Ne). (d) Close-up of the facies showing *Nereites missouriensis* (Ne) and *Teichichnus rectus* (Te). The red color results from oxidization.

deposition during storm events. Some storm-generated layers may have been reworked by bioturbation, resulting in intervals of sandy siltstone to silty sandstone, where discrete beds cannot be identified. The concentration of *Chondrites* isp. near the top of micro-HCS sandstone beds may indicate the burial of large amounts of organic detritus during storms (Vossler and Pemberton, 1989). The decreased proportion of sandstone and siltstone ratio compared to Facies 5 suggests the alternation of less frequent and lower-energy storm events with suspension fallout. Facies 6 is deposited between storm wave base and fair-weather wave base in an upper-offshore environment.

3.8 Facies 7: Highly Bioturbated Siltstone Facies (Figure 16a-b)

3.8.1 Description

This facies is composed of greyish green, massive, and highly bioturbated siltstone. Sandstone lenses (< 2 cm) rarely occur. Pyrite is commonly disseminated, and brachiopod shell fragments are locally present. The bioturbation index is 5 to 6, but identification of discrete ichnotaxa is difficult, except for *Phycosiphon incertum* and local *Nereites missouriensis*. The interval thickness of Facies 7 is up to about 1.2 m.

3.8.2 Interpretation

Facies 7 suggests sedimentation from suspension fallout in an overall low-energy environment. The intense bioturbation may have contributed to the massive appearance of Facies 7. Except for the rare thinly laminated sandstone lenses which record rare disruption by distal storms, the bulk of this facies represents background deposition (e.g., suspension fallout). The local presence of parallel-laminated sandstone lenses suggests deposition above the storm wave base, and the higher silt content in comparison with Facies 6 indicates deposition in a much lower-energy setting. Facies 7 is interpreted as having been deposited immediately above storm

wave base in a lower-offshore environment.

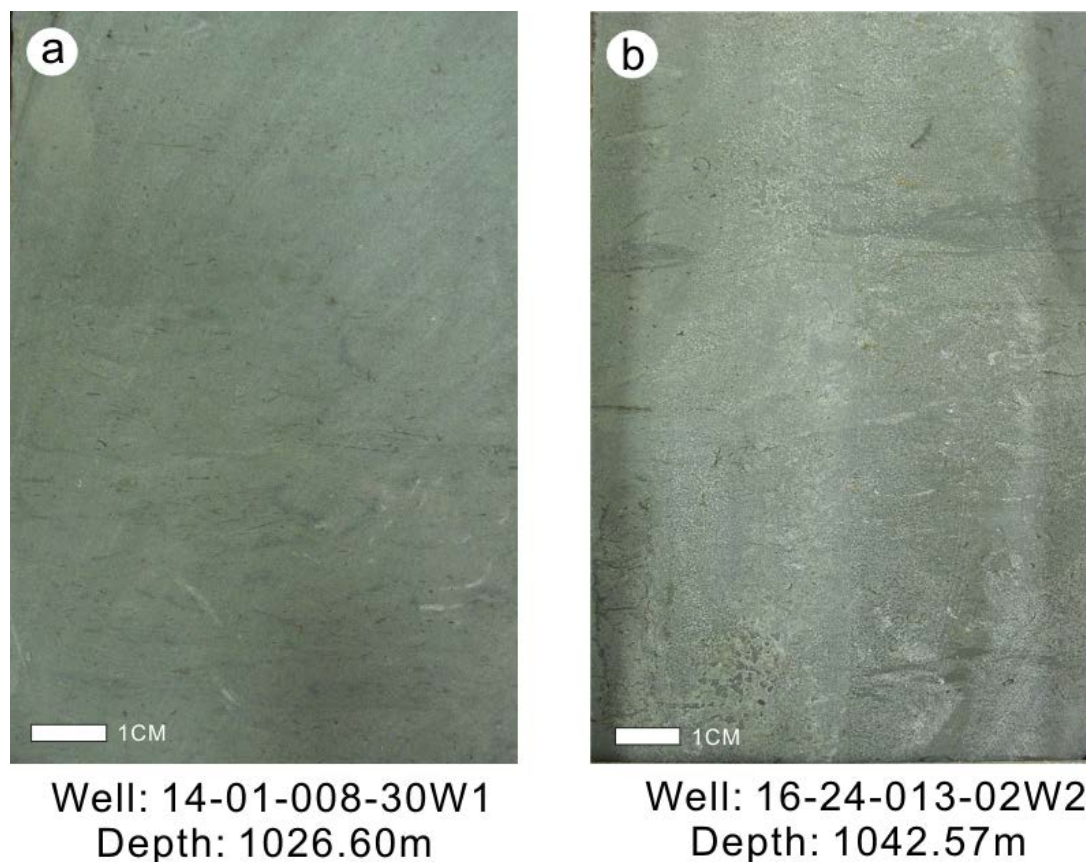


Figure 16- Core photos of Facies 7: Highly bioturbated siltstone. (a) and (b) Note the massive appearance of the facies due to high bioturbation intensity, which makes recognition of discrete ichnotaxa quite difficult.

3.9 Facies 8: Black Shale Facies (Figure 17a-b)

3.9.1 Description

This facies is composed of massive to locally parallel-laminated, organic-rich, and fissile black shale. Fractures that are filled with pyrite and calcite locally occur. Disseminated pyrite and pyrite concretions are present in places. Conodonts are observed from the upper member in some core logged for this thesis research. Other body fossils, such as brachiopods, fish scales, echinoderm fragments (e.g., crinoid ossicles), plant fragments, and rare arthropod remains are also documented by previous studies (Fuller, 1956; Brindle, 1960; Christopher, 1961; Thrasher, 1985;

Karma, 1991b). Bioturbation is commonly absent in the black shale members, except for local observation of *Chondrites* and *Thalassinoides* near the top of the lower shale member in cores, and *Chondrites*, *Zoophycos*, and *Phycosiphon* in outcrops of the equivalent Exshaw Formation at Crowsnest Lake, Alberta (Angulo et al., 2008). The interval thickness of upper black shale varies from 0.6 m to about 4.0 m, and the interval thickness of lower black shale ranges from less than 1.0 m to 9.0 m (picked from gamma-ray logs). The contact between Facies 7 and Facies 8 is sharp, but conformable.

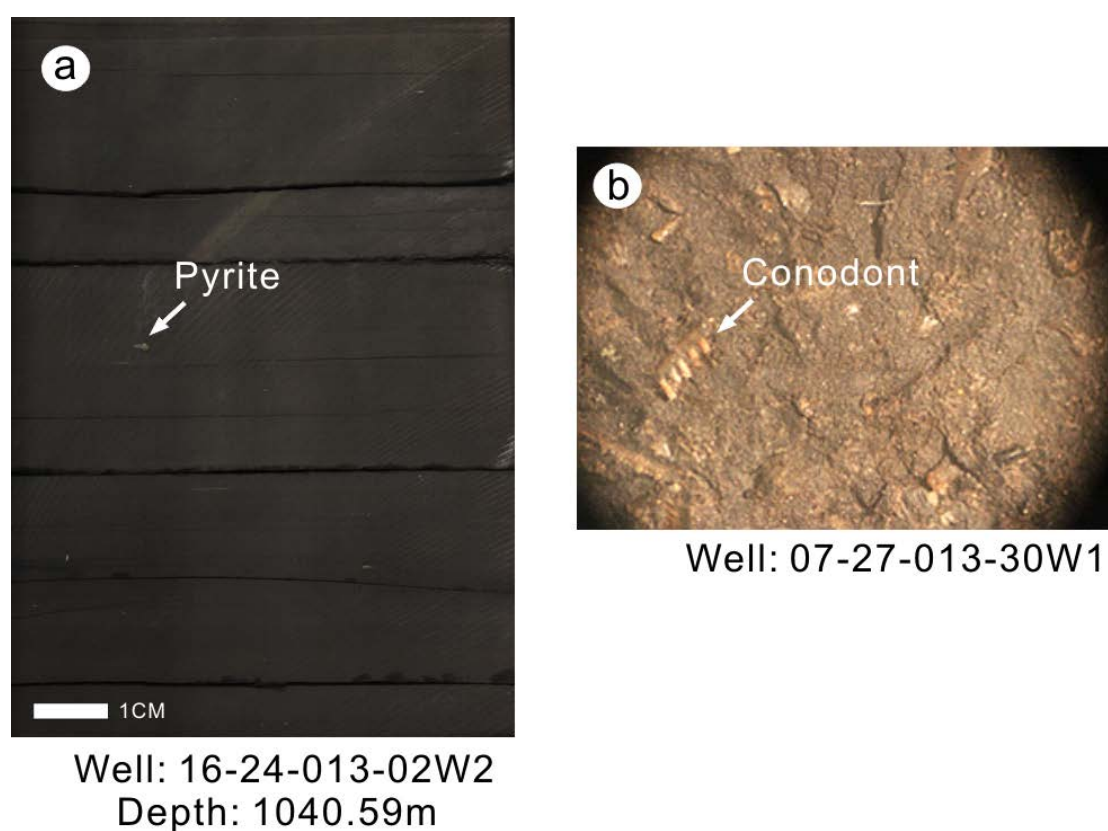


Figure 17- Core photos of Facies 8: Black shale. (a) General view of the facies showing pyrite. Note the absence of bioturbation. (b) Bedding-plane view of the black shale showing conodont fragments (from the upper black shale).

3.9.2 Interpretation

Facies 8 represents sedimentation from suspension fallout in a low-energy setting without evidence of oscillatory processes. The local presence of vertical or high-angle

fractures either results from local tectonism (Kreis et al., 2006) or the pressure increase in the trapped fluid during the conversion from organic matters to oil and gas. The black color and lack of bioturbation indicate that sedimentation took place in an anoxic environment, with the only exception of the beds near the top of lower member, which contain *Chondrites* and *Thalassinoides*, suggesting local dysoxic condition. However, according to Egenhoff and Fishman (2013), burrows are present in the upper black shale member in North Dakota, therefore suggesting that dysoxic conditions were prevailing during deposition in this area. Facies 8 is deposited below the storm wave base in a shelf environment.

4. DEPOSITIONAL MODEL

4.1 Open-marine Facies Association

The open-marine facies association corresponds to the upper black shale member and unit C of the middle member in the stratigraphic subdivision (Figure 3). It contains five facies, representing different subenvironments located along the depositional profile of a low-energy wave-influenced shallow-marine setting (Figure 18). The shale (Facies 8) represents a shelf environment, which is located below the storm wave base. The highly bioturbated siltstone (Facies 7) records deposition in lower offshore, which is located right above the storm wave base. The interbedded highly bioturbated sandy siltstone and micro-HCS very fine-grained sandstone (Facies 6) represents the upper offshore, which is located between the storm wave base and fair weather wave base. The highly bioturbated interbedded very fine-grained sandstone and siltstone (Facies 5) was formed in offshore transition, which is a narrow zone right below the fair weather wave base. The granule- and pebble-bearing sandy siltstone, with shell fragments (Facies 4) represents a transgressive lag, which is formed locally during transgression. Where Facies 4 is present, the contact with the underlying brackish-water marginal-marine environment is erosional, otherwise, the contact between Facies 5 or Facies 6 with the underlying brackish-water interval can be sharp or gradational. Except for that, the contact between the upper black shale of Facies 8 and the lower offshore deposits of Facies 7 is sharp but conformable; all the contacts between each of the open-marine facies are gradational. The rare sandy deposits in the offshore-transition, lower-and upper-offshore environment represent deposition from storms. However, the overall scarcity of discrete tempestite layers and wave-generated structures is mostly due to intense biogenic reworking.

An ancient analogue for the open-marine facies association is the Permian Palermo Formation in the Paraná Basin, southern Brazil, which is also interpreted as transgressive deposits from the offshore transition to shelf in a wave-dominated open marine environment. These deposits rest on top of a wave ravinement surface that

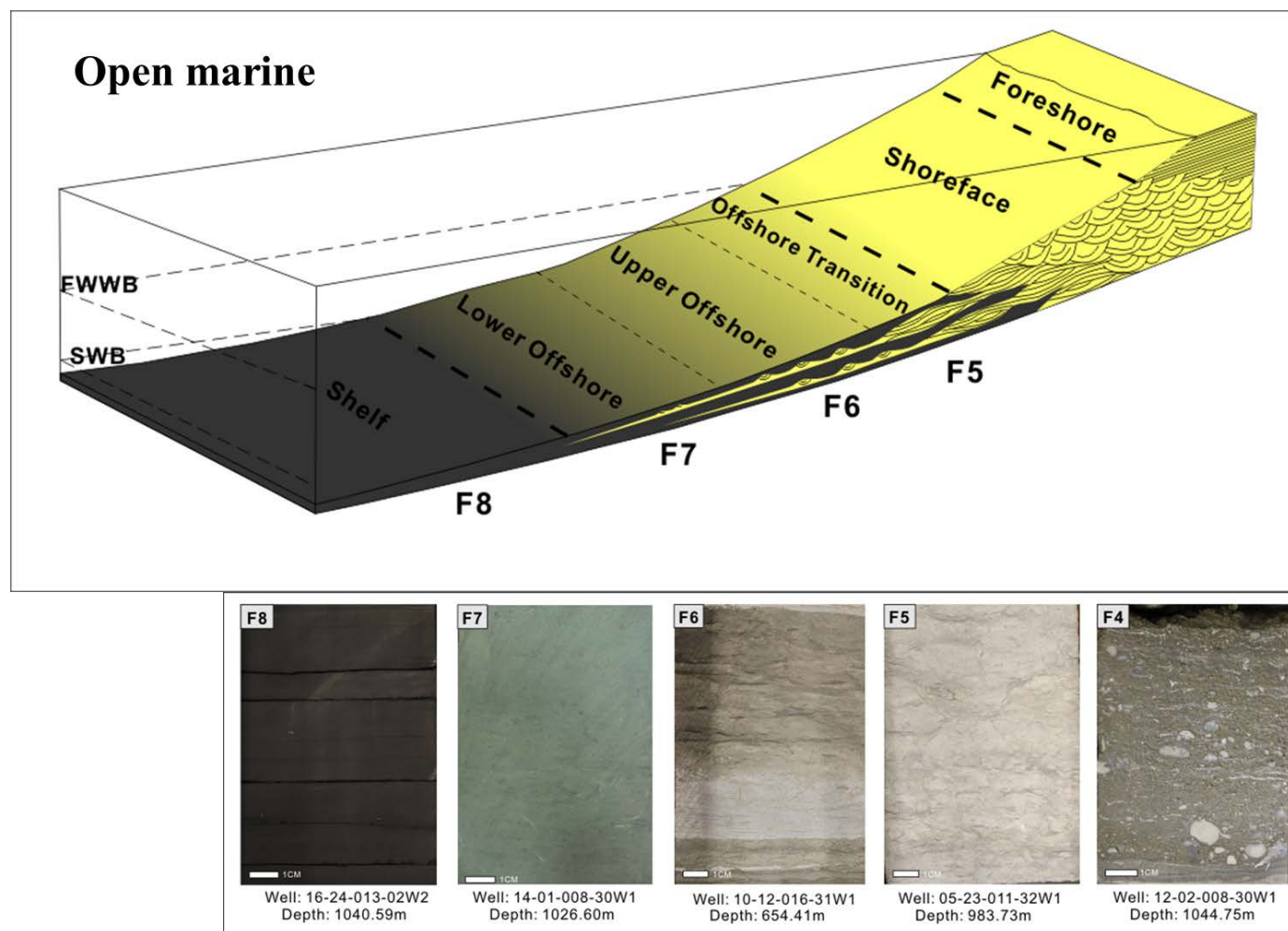


Figure 18- Depositional model for the open-marine facies association (modified from Proverbs et al., 2010).

truncates the underlying brackish-water marginal-marine deposits (Buatois et al., 2007). The offshore-transition and upper-offshore deposits of the Palermo Formation are similar to the Bakken Formation, being intensively bioturbated. However, the lower-offshore deposits of the Palermo Formation are highly variable, ranging from intervals with discrete storm beds having well-preserved primary sedimentary structures to others that are totally homogenized by biogenic reworking (Buatois et al., 2007).

As for the modern analogue, the wave- and storm-dominated shelf off the east Texas Coast, Gulf of Mexico, is a potential candidate. Similar to the Bakken, the upper offshore deposits of the east Texas Coast mainly consist of moderately bioturbated muds with intercalated very thin beds of very fine-grained sands which are dominated by very thin lamination and recognized as tempestites; the lower-offshore muds are homogenized with only rare discrete sand layers (Siringan, 1994; Plint, 2010).

4.2 Marginal-Marine Facies Association

The brackish-water marginal-marine facies association is overlain by the open-marine deposits, and corresponding to unit B2 and B3 of the middle member in the stratigraphic subdivision (Figure 3). It contains three facies representing different subenvironments of a restricted embayment with limited or intermittent connection to the open marine in the west (MacEachern and Gingras, 2007; Buatois and Mángano, 2011; Angulo and Buatois, 2012a) (Figure 19). Parallel-laminated very fine-grained sandstone and muddy siltstone (Facies 3) represents a distal bay, relatively far from fluvial discharge. Thinly parallel-laminated very fine-grained sandstone and siltstone (subfacies 2B) suggests bay-margin deposits, probably closed to the mouth of fluvial systems, and wavy-to flaser-bedded very fine-grained sandstone (subfacies 2A) records bay-margin deposits most likely around the back of a barrier bar. The planar cross-stratified fine-grained sandstone (Facies 1) represents the barrier-bar deposits

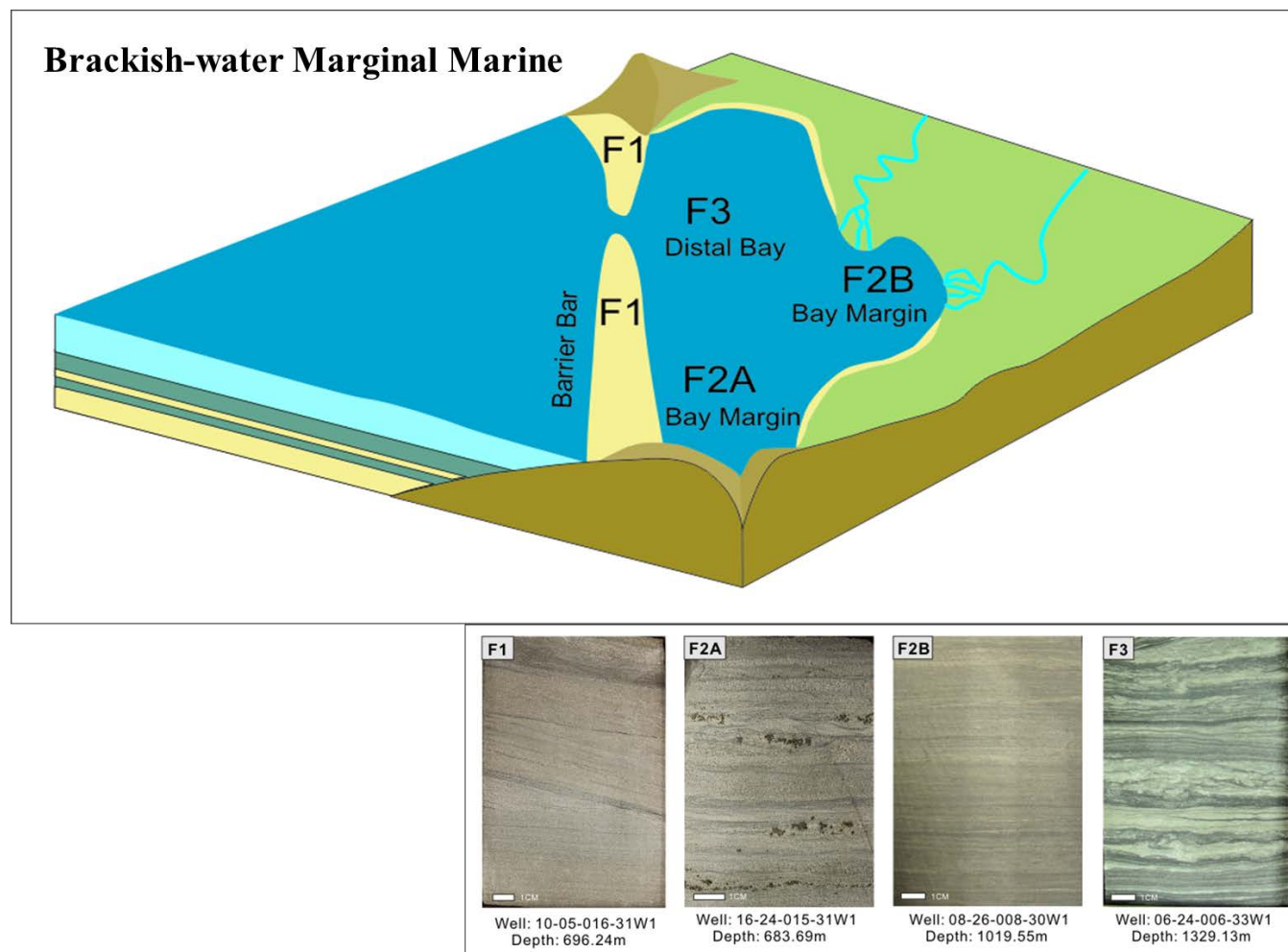


Figure 19- Depositional model for the brackish-water marginal-marine facies association (modified from Buatois and Mángano, 2011).

that separate the embayment from the open-marine environment. The brackish-water marginal-marine deposits overlie the underlying lower Bakken shale or Torquay Formation unconformably. The contacts between each of the brackish-water marginal-marine facies can be sharp or gradational, but all conformable.

The tidal influence is suggested by heterolithic lamination/bedding, wavy and flaser bedding, and mudstone drapes, and this is explained as resulting from the embayment topography, where tidal currents are amplified and the preservation potential of tidal deposits is enhanced (Dalrymple, 2010). The presence of syneresis cracks indicates salinity fluctuation (Burst, 1965; MacEachern and Pemberton, 1994). In addition, the deposits are also characterized by small trace fossils, low bioturbation and ichnodiversity which will be further discussed in the following session. All these characteristics suggest that deposition took place in stressful marginal-marine environments instead of open-marine environments.

According to Yoshida et al. (2004), an embayment is classified into a wave-dominated setting, which is a restricted bay with brackish-water conditions; and a tide-dominated setting, which is typically an open bay with normal marine-water conditions. An example of a tide-dominated normal-marine open embayment is the middle part of the Lower Cretaceous Woburn Sands in southern England (Yoshida et al., 2004), which is dominated by the alternation of trough or planar cross-bedded sandstone and bioturbated sandstone, with strong tidal indicators and a normal-marine signature in the trace fossil assemblages. The Bakken marginal-marine facies association clearly fits with the brackish-water restricted embayment as for the classification of Yoshida et al. (2004), albeit with tidal influence. A few ancient analogues of restricted bays are documented in the Lower Cretaceous strata in Alberta and Saskatchewan, including the Grand Rapids Formation in the Cold Lake area of Alberta (Beynon et al., 1988; Beynon, 1991), the Paddy Member of the Peace River area and west-central Alberta (Smith et al., 1984), and the Waseca Formation in the Lloydminster area of Saskatchewan (MacEachern, 1984, 1986).

One of the modern analogues is probably the Holocene Galveston Bay on the

Texas coast (Rehkemper, 1969), which has a barrier separating the bay from the open marine. Although displaying more bioturbation and ichnodiversity compared to the Bakken Formation, the Galveston Bay deposits are still characterized by brackish-water assemblages of biogenic structures.

5. ICHNOLOGIC ANALYSIS

5.1 Open-marine Facies Association (Figure 20)

The open-marine facies are generally highly bioturbated, except for the black shale of Facies 8. Facies 8 is mostly free of bioturbation, most likely resulting from its anoxic to locally dysoxic condition, where animals can hardly colonize. Facies 7 is almost completely bioturbated, and the identification of individual trace fossils is difficult, but *Phycosiphon incertum* and *Nereites missouriensis* can be locally recognized. The dominance of a deposit feeding strategy is consistent with the overall low-energy setting where organic particles are kept in the sediment. The presence of *Nereites missouriensis* whose horizontal parts are closely spaced probably indicates high content of food supply within the sediment. Facies 7 is characterized by the distal *Cruziana* Ichnofacies as it contains a significant number of grazing trails and specialized feeding traces. Facies 6 has a bioturbation index of 4-5 for the fair-weather deposits, and includes feeding traces, such as *Phycosiphon incertum*, *Asterosoma* isp., *Teichichnus rectus*, and *Planolites montanus*, dwelling structures, namely *Palaeophycus tubularis*, and also grazing trails, such as *Nereites missouriensis*. Although Facies 6 displays highly abundant trace fossils, the ichnodiversity is moderate, and no vertical dwelling structures from suspension feeders are present. The trace fossils are overwhelmingly produced by selective deposit feeding, which is the dominant strategy for elements of distal *Cruziana* Ichnofacies (Buatois et al., 2013). In contrast, the archetypal *Cruziana* Ichnofacies generally contains more trophic types (Buatois et al., 2013). As for the storm deposits of Facies 6, they display very low intensity of bioturbation (BI = 0-1), the limiting factor is most likely the rapid sedimentation rate. Occasionally, *Chondrites* isp. is observed near the top of storm micro-HCS deposits, which indicates post-storm colonization by opportunistic organisms (Frey and Goldring, 1992). The assemblage of Facies 6 represents the distal *Cruziana* Ichnofacies. Facies 5 also has a bioturbation

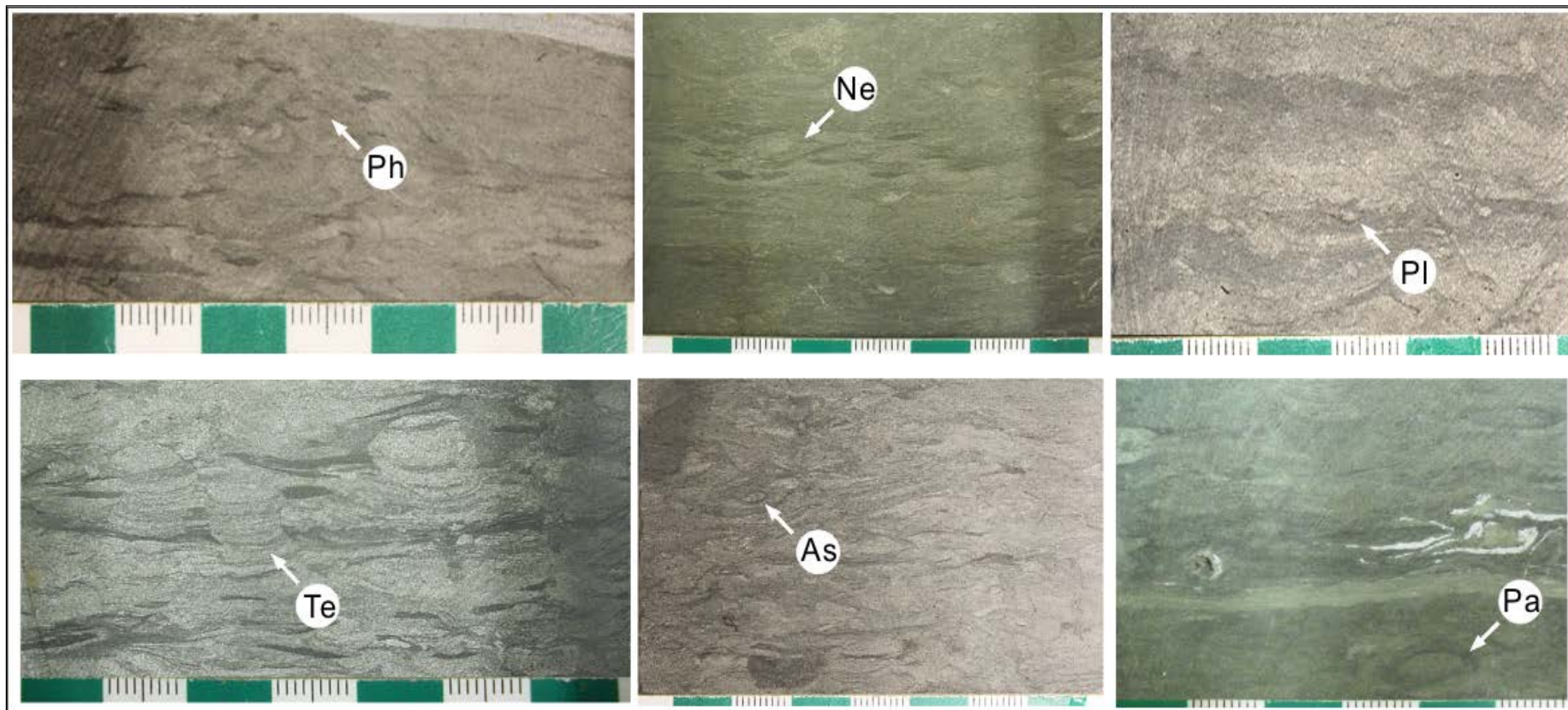


Figure 20- Some core intervals showing the distal *Cruziana* Ichnofacies of the Bakken Formation in the southeastern corner of Saskatchewan. The ichnofauna includes *Phycosiphon incertum* (Ph), *Nereites missouriensis* (Ne), *Planolites montanus* (Pl), *Teichichnus rectus* (Te), *Asterosoma* isp. (As), and *Palaeophycus tubularis* (Pa).

index of 4-5, including feeding traces, such as *Phycosiphon incertum*, *Asterosoma* isp. and *Planolites montanus*, dwelling structures, such as *Palaeophycus tubularis*, and grazing trails, such as *Nereites missouriensis*. As in the case of facies 6, the assemblage is similar to the *Cruziana* Ichnofacies, but dominant structures are produced by selective deposits feeders (e.g., *Phycosiphon*, *Planolites* and *Nereites*), and no vertical structures produced by suspension feeders are present. It displays lower diversity than the archetypal *Cruziana* Ichnofacies and a dominance of ichnotaxa common in distal *Cruziana* Ichnofacies.

Generally, the open-marine environment is characterized by the distal *Cruziana* Ichnofacies (Figure 20). The lack of shallow-tier ichnofossils may result from their lower preservation potential in a highly bioturbated sediment, since the deep-tier structures commonly obliterate those emplaced in shallower tiers due to upward migration as a response to vertical accretion of the sea floor.

Typically, for the clastic shallow marine onshore-offshore ichnofacies model (MacEachern and Pemberton 1992; Pemberton et al., 2001; Buatois et al., 2002; Gaillard and Racheboeuf, 2006; MacEachern et al., 2007; Buatois and Mángano, 2011), the foreshore is characterized by *Macaronichnus* association or the *Skolithos* Ichnofacies, the upper and middle shoreface by the *Skolithos* Ichnofacies, the lower shoreface by the proximal *Cruziana* Ichnofacies, the offshore transition and upper offshore by the archetypal *Cruziana* Ichnofacies, the lower offshore by the distal *Cruziana* Ichnofacies and the shelf by the *Zoophycos* Ichnofacies. However, for the Bakken Formation in the southeastern corner of Saskatchewan, the distal *Cruziana* Ichnofacies expands landward into more proximal environments of the upper offshore and offshore transition. This is explained as the result of Late Devonian mass extinction, during which the shallow-marine communities were more seriously affected than the relatively deeper-water ones, and the available niches in nearshore and proximal offshore allowed for the landward expansion of deeper-water communities (Buatois et al., 2013). This phenomenon also emphasizes the importance of trophic type as a selective trait during mass extinction, since the communities are

overwhelmingly dominated by selective deposit feeders (Buatois et al., 2013).

The Lower Triassic Montney Formation in northeast British Columbia is interpreted as deposited from the shelf to the offshore transition after the end-Permian mass extinction (Zonneveld et al., 2010), which is a similar context to that of the Bakken. However, in contrast to the intense bioturbation of the Bakken Formation, the lower and upper-offshore deposits of the Montney Formation are mostly devoid of bioturbation, with only the local presence of escape trace fossils in sandstone beds. In the offshore-transition environment, only escape trace fossils and the simple feeding trace *Planolites* are present. Besides, the Montney deposits are overwhelmingly dominated by black color, from shelf to offshore transition deposits. Compared to the open-marine deposits of the Bakken Formation, this extremely unique phenomenon of low bioturbation and ichnofauna content in the Montney Formation also resulted from other harsh conditions, such as volcanic eruption, global warming, coastal upwelling, anoxic and acidic oceanographic environment, which seem to represent the probable cause(s) of the end-Permian mass extinction (Woods, 2014).

5.2 Marginal-marine Facies Association (Figure 21)

Compared to the open-marine environment, the marginal-marine environment generally displays a lower bioturbation index, smaller size and also lower ichnodiversity and abundance. The most significant controlling factor for the marginal-marine embayment is the salinity variation (Buatois and Mángano, 2011), and animals that can survive are those who are highly tolerant to salinity changes. To buffer the salinity variation, in addition to reduced size, burrowing is also a common strategy. The most common trace fossil in the marginal-marine environment is *Planolites montanus*, and other ichnotaxa, such as *Palaeophycus tubularis*, *Rosselia* isp. and *Teichichnus rectus* only occur locally in the distal-bay deposits of Facies 3, which is relatively far from the area of fluvial discharge and experiences less salinity fluctuation. Being the most hospitable subenvironment for animal colonization in the

embayment, it probably also indicates the distal bay holds abundant food supply and overall low sedimentation rate (Gingras et al., 2012). The barrier-bar deposits of the bay mouth (Facies 1) are devoid of bioturbation; besides the salinity changes, the erosion typical of this high-energy setting characterized by migration of dunes is also too stressful for animals to colonize. The bay-margin deposits of Facies 2A and 2B only consist of sporadically distributed, small *Planolites montanus*, which is morphologically a very simple burrow produced by deposit feeders. Salinity fluctuation is probably the dominant influence, therefore, reduced size and a burrowing strategy are adopted. Turbidity is also a potential stress for the embayment assemblage, as it is dominated by deposit feeders in the absence of suspension feeders (MacEachern et al., 2005; Buatois and Mángano, 2011). Generally, the marginal-marine environment is represented by lower ichnodiversity and abundance, and characterized by the depauperate *Cruziana* Ichnofacies (Figure 21).

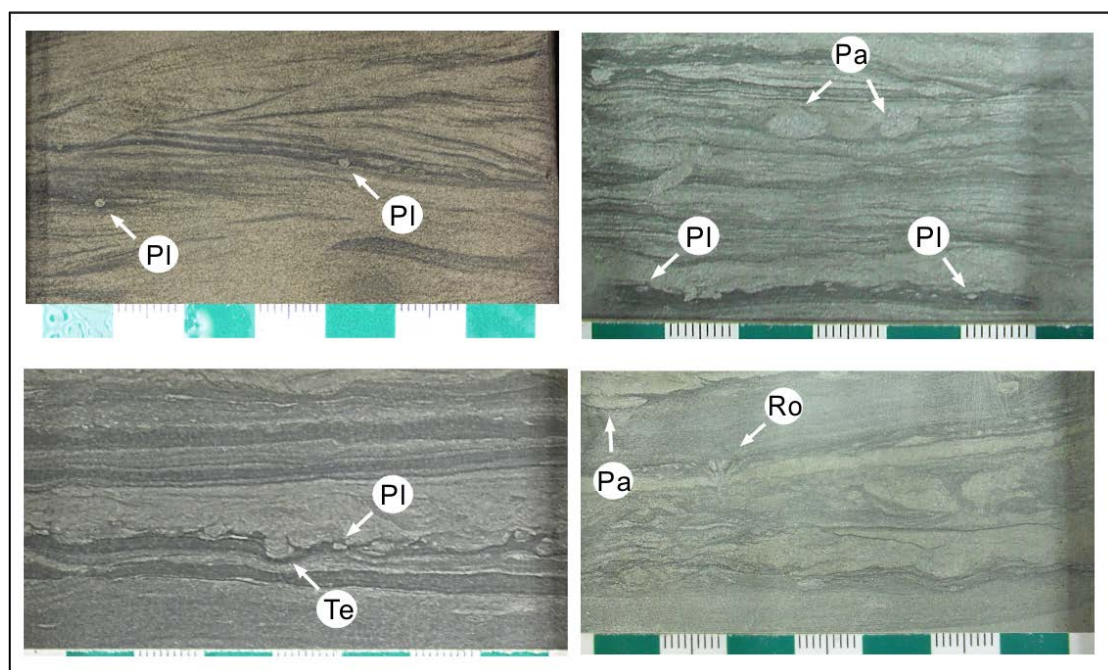


Figure 21- Some core intervals showing the depauperate *Cruziana* Ichnofacies of the Bakken Formation in the southeastern corner of Saskatchewan. The ichnofauna includes *Planolites montanus* (PI), *Palaeophycus tubularis*, *Teichichnus rectus* (Te), and probably *Rosselia* isp.

6. SEDIMENTARY FACIES DISTRIBUTION

Isochore maps were made for Facies 8 (shelf-upper member), Facies 7 (lower offshore), Facies 6 (upper offshore), Facies 5 (offshore transition) of the open-marine environment; and Facies 3 (distal bay), Facies 2B (bay margin), Facies 2A (bay margin) of the brackish-water marginal-marine environment. Because of their limited representation in the cores studied, no isochore maps were produced for Facies 8 (shelf-lower member), Facies 4 (lag) and Facies 1 (barrier bar). To make it more accurately, the isochore map of Facies 8 is based on well log data. The isochore maps for all the other facies are constructed based on core thickness.

Localized salt dissolution and collapse of the underlying Middle Devonian Prairie Evaporite had an important influence on the thickness of the Bakken Formation, creating some anomalously thickened zones, as shown in the northernmost region of this study area (Figure 22; Figure 23) (Christopher, 1961; Kreis et al., 2006; Kohlruss and Nickel, 2009; Angulo and Buatois, 2010). Regardless of those anomalously thickened zones, facies distribution displays some general trends.

Isochore maps of the open-marine facies (Figure 22) show widespread distribution, covering most of the study area. The only exception is the transgressive lag (Facies 4), which is only present in a few cores of the southeastern to eastern part of the study area. As shown in the isochore maps, more distal deposits of the shelf and lower offshore tend to be thicker in the west, whereas the more proximal deposits of upper offshore and offshore transition tend to be thicker in the east, suggesting a N-S trending paleo-shoreline.

Isochore maps of the marginal-marine facies (Figure 23) also show widespread distribution, covering a significant part of the study area. The bay-margin deposits (Facies 2A and Facies 2B) tend to be thicker towards the west, whereas the distal-bay deposits (Facies 3) tend to be thicker towards the east, which is probably because of the irregular paleotopography which resulted from the sea level fall. The thick zone in the northernmost area reflects salt collapse.

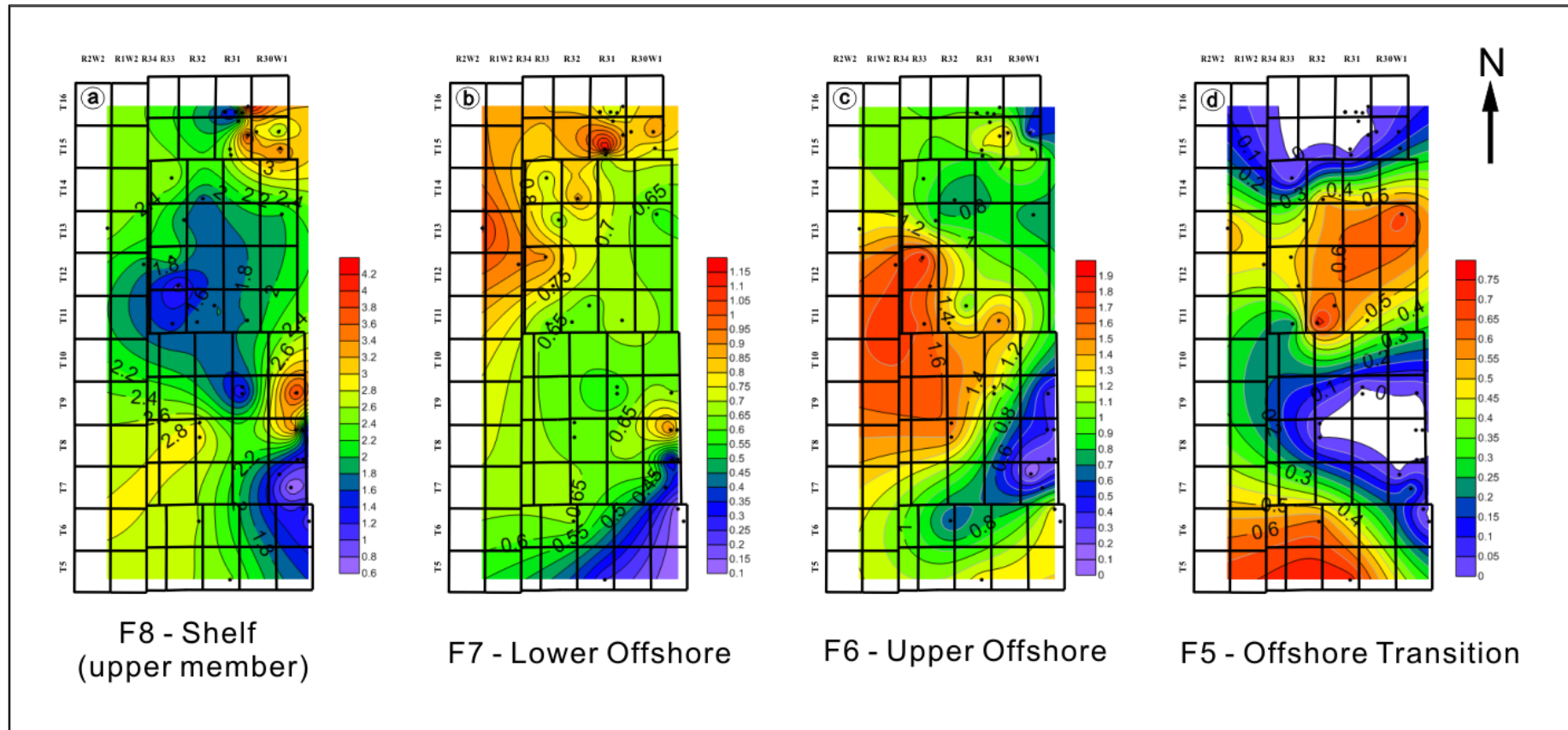


Figure 22- Isochore maps of the open-marine sedimentary facies (contours in meter).

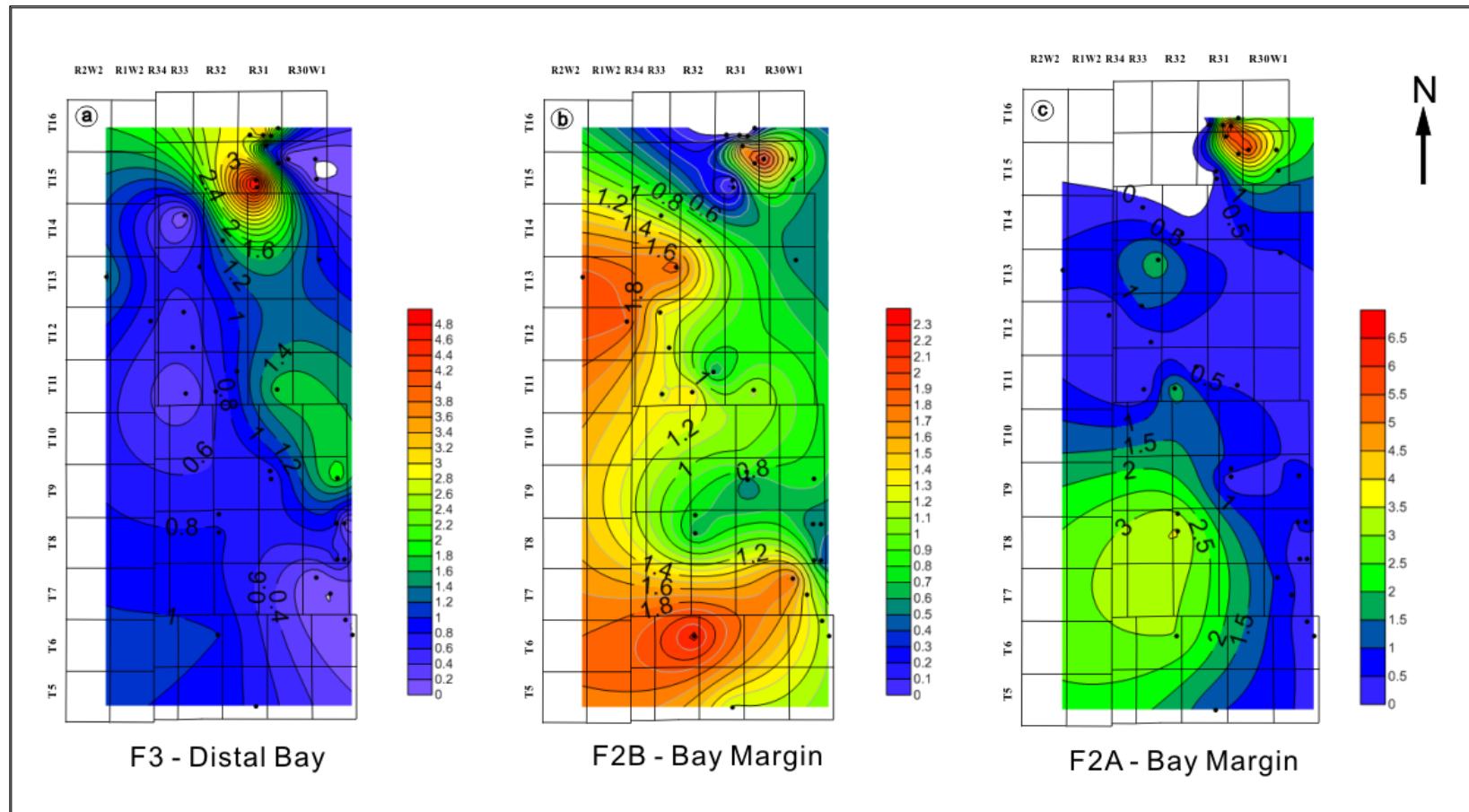


Figure 23- Isochore maps of the brackish-water marginal-marine sedimentary facies (contours in meter).

Figure 22-Continued. (a) Isochore map of Facies 8 (shelf-upper member). Facies 8 is present over the whole study area. The thickness ranges from 0.6 to about 4m. Except for localized thickened zone resulting from salt collapse, the general trend should be thicker towards west-southwest of this study area. (b) Isochore map of Facies 7 (lower offshore). Facies 7 is distributed across the entire study area. The thickness obviously shows thickening trend from 0.1 m in the southeast to about 1.2 m in the west-northwest, except for the local thickened zone resulting from salt collapse. (c) Isochore map of Facies 6 (upper offshore). Facies 6 is widespread across the whole study area, with the relatively thicker zone in the west, and thinner zone in the east of the study area. The thickness varies from 0.1 to 1.9 m. (d) Isochore map of Facies 5 (offshore transition). Facies 5 also covers most of this study area, with only two local zones where it is absent. Two thicken zones are located in the northeast and south of this study area. The thickness ranges from 0 to 0.75 m.

Figure 23-Continued. (a) Isochore map of Facies 3 (distal bay). Facies 3 is widespread in the most of study area. The isochore map shows a thick zone in the east and the thickness varies from 0 to almost 5 m. (b) Isochore map of Facies 2B (bay margin). Facies 2B covers the entire study area except for a tiny zone near north margin of the study area. It shows obviously thickening towards west, and the thickness is up to 2.4 m. (c) Isochore map of Facies 2A (bay margin). Facies 2A is also regional present throughout the study area, with only the exception being in the northeast edge of the mapping area. The isochore map shows thickening trend to west-southwest. The thickness ranges from 0 to 6.5 m.

7. SEQUENCE-STRATIGRAPHIC ANALYSIS

During the Late Devonian, most of the Williston Basin and eastern cratonic platform were exposed to erosion and reworking, resulting from the sea-level fall which produced the Acadian unconformity (Angulo et al., 2008). However, the relatively deeper center of the Williston Basin and the Prophet trough experienced little or no reworking (Smith and Bustin, 2000). In Saskatchewan, the Acadian unconformity corresponds to the contact between the Bakken Formation/Big Valley Formation and the underlying Torquay Formation (Nickel, 2010).

According to Angulo and Buatois (2012a) (Figure 4), the Bakken Formation in southeastern Saskatchewan contains three systems tracts: a basal transgressive systems tract which includes the lower part of lower Bakken shale (Facies 1 of these authors), a highstand systems tract which includes the uppermost part of lower Bakken shale and the lower open-marine interval of the middle member (Facies 1 to 5 of these authors), and an upper transgressive systems tract which include the brackish-water marginal-marine interval and the upper open-marine interval of the middle member, and the upper Bakken shale (Facies 6 to 11, Facies 3B, and Facies 1 of these authors). The black shale of the basal transgressive systems tract, together with the underlying Big Valley strata whose presence is controlled primarily by available accommodation space, overlies the Acadian unconformity, and records the latest Devonian sea-level rise (Johnson et al., 1985). Therefore, the basal contact of the lower Bakken shale or the Big Valley Formation (if present) with the underlying Torquay Formation is considered to be a coplanar surface or amalgamated sequence boundary and transgressive surface. The maximum flooding surface, which marks the top of the basal transgressive systems tract, is near the top of the lower Bakken shale (Angulo et al., 2008; Angulo and Buatois, 2012a).

In much of the southeastern corner of Saskatchewan, which is in a more proximal location, as well as being uplifted before deposition of the Bakken Formation, most of the basal transgressive systems tract deposits (lower part of lower

Bakken shale) and highstand systems tract deposits (uppermost part of lower Bakken shale and lower open-marine interval) have been eroded because of the subsequent drastic sea level fall. Any deposits of the falling stage systems tract may also have been eroded at the same time. The absence of these strata is not considered to be due to non-deposition resulting from limited onlap, because the lower Bakken shale is also present in a more eastern/proximal area in Manitoba (Christopher, 1961).

Subsequently, the sea level started to rise, but no lowstand fluvial deposits are observed, indicating this study area is probably located somewhere within interfluvial areas and/or affected by continuous sediment bypass at that time. At a later stage, the rapid sea level rise outpaced the rate of sediment supply, resulting in the formation of a brackish-water marginal-marine embayment (Facies 1-3) that flooded the pre-existing topography during the early transgression. The base of the marginal-marine interval is represented by a coplanar surface or amalgamated sequence boundary and transgressive surface.

According to Sandberg et al. (2002), there is a general sea-level fall across the Devonian-Carboniferous boundary due to the southern Hemisphere glaciation. Therefore, this coplanar surface may represent the Devonian-Carboniferous boundary (Angulo et al., 2008; Angulo and Buatois, 2012a). According to Angulo et al. (2008), the surface reflects an abrupt decrease in diversity and abundance of trace fossils, which suggests a sudden change in environmental parameters (e.g., salinity), from the previous open-marine conditions of the highstand systems tract to marginal-marine restricted setting of the overlying transgressive systems tract. Lowstand systems tract fluvial deposits have neither been identified in the Bakken cores by Angulo and Buatois (2012a), nor in the course of this investigation.

As the transgression progressed, the shoreline continued moving towards the land and the shelf area enlarged, along with a marked decrease of sediment influx into the basin and cannibalization of previous marginal-marine deposits by wave ravinement. In the southeastern to eastern part of the study area, a transgressive lag was formed (Facies 4) directly above the brackish-water marginal-marine deposits.

The erosional contact between the transgressive lag and the underlying brackish-water marginal-marine deposits is a wave ravinement surface (Cattaneo and Steel, 2003). After the deposition of the transgressive lag, the open-marine environment was re-established, and an overall fining-upward, retrogradational stacking unit, including offshore transition (Facies 5), upper offshore (Facies 6), lower offshore (Facies 7) and shelf (Facies 8) was deposited, recording the late stage of the transgression. Where transgressive lag deposits are not present, the open-marine deposits directly overlie the marginal-marine deposits, and the contact can be gradational or sharp. Therefore, where the lower Bakken shale and the lower open-marine interval are not preserved, the entire Bakken succession records deposition during a transgression, representing a transgressive systems tract. This situation is quite common in the southeastern corner of Saskatchewan (Figure 24; Figure 25).

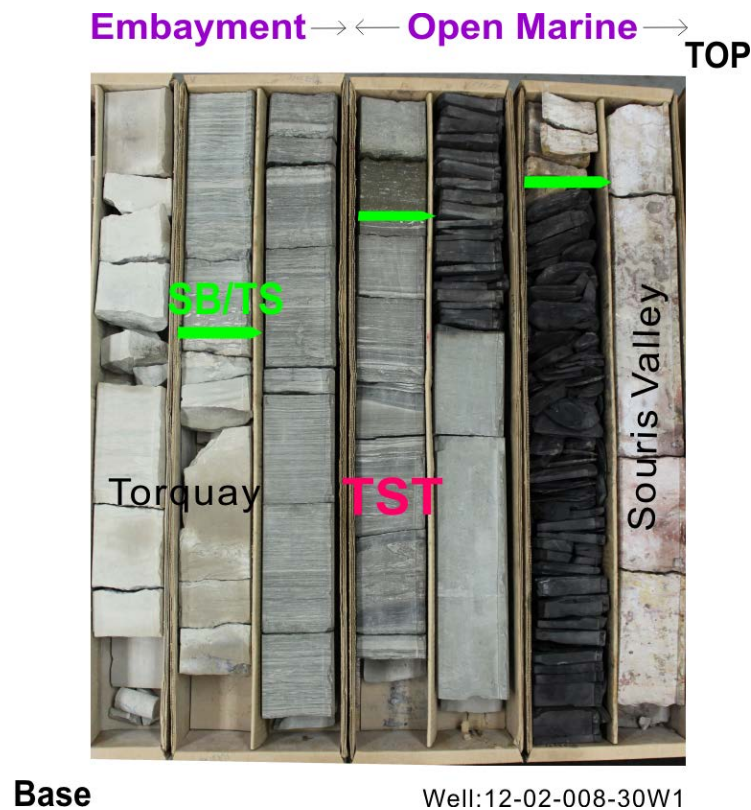


Figure 24- Core photo (well: 12-02-008-30W1) showing the open-marine and brackish-water marginal marine facies association, as well as the interpretation of sequence stratigraphy for most common situation of this thesis research area. TST: transgressive systems tract. SB/TS: sequence boundary/transgressive surface.

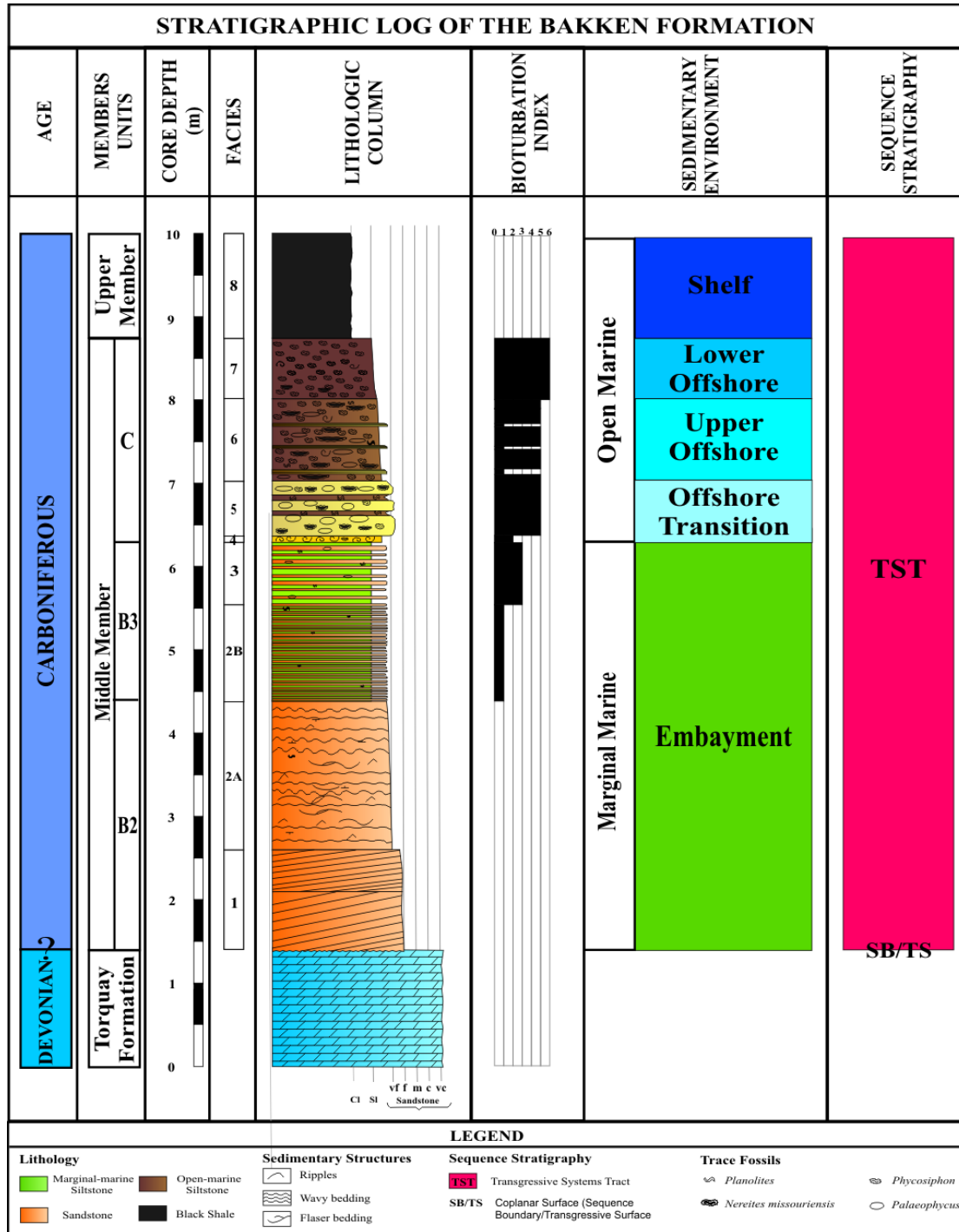


Figure 25- The most common composite log showing lithology, sedimentary structures, trace fossils, interpretation of sedimentary facies, sedimentary environments and sequence stratigraphy of the Bakken Formation in the southeastern corner of Saskatchewan (after Angulo and Buatois, 2012a).

In some areas, such as those affected by salt collapse (e.g., the Rocanville oil-field area), the lower part of the lower Bakken shale, which records deposition during the basal transgression, is preserved. This occurs because it was not entirely eroded during the sea-level fall, as a result of its relatively low paleo-topography.

In this case, the preserved part of lower Bakken shale, which belongs to the basal transgressive systems tract, is unconformably overlain by the brackish-water marginal-marine and open-marine strata that were deposited during the upper transgression (Figure 26). The whole succession records deposition during two transgressions, representing two transgressive systems separated by a coplanar surface. Figure 27 shows the most complete composite log of the Bakken Formation in the southeastern corner of Saskatchewan.

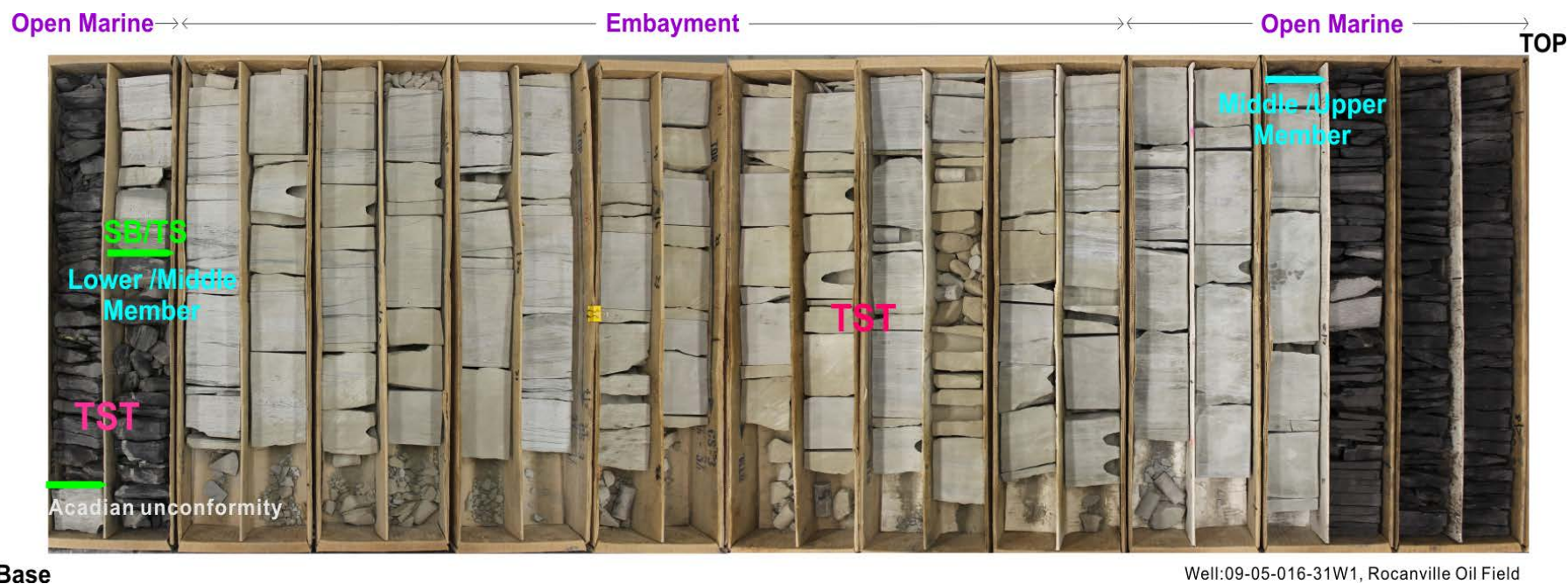


Figure 26- Core photo (well: 09-05-016-31W1) showing the open-marine and brackish-water marginal marine facies association, as well as the interpretation of sequence stratigraphy for most complete situation of this thesis research area. TST: transgressive systems tract. SB/TS: sequence boundary/transgressive surface.

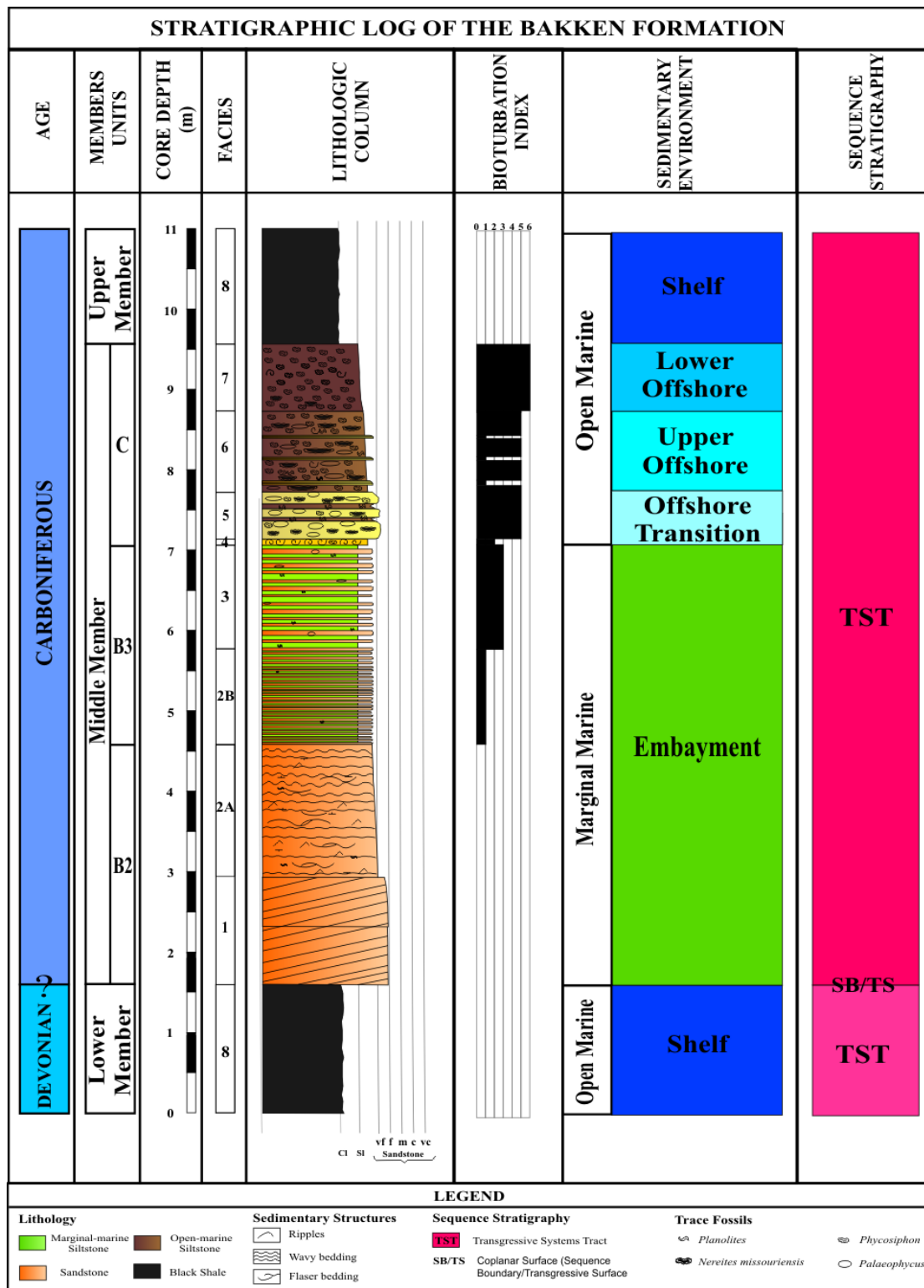


Figure 27- The most complete composite log showing lithology, sedimentary structures, trace fossils, interpretation of sedimentary facies, sedimentary environments and sequence stratigraphy of the Bakken Formation in the southeastern corner of Saskatchewan (after Angulo and Buatois, 2012a).

8. DISCUSSION

According to Angulo and Buatois (2012a), in southeastern Saskatchewan, the Bakken Formation is divided into three intervals from bottom to top: a lower open-marine interval, including Facies 1 (black shale), Facies 2 (highly bioturbated siltstone), Facies 3A (highly bioturbated sandy siltstone), Facies 4 (highly bioturbated interbedded sandstone and siltstone), Facies 5 (highly bioturbated sandstone); a middle brackish-water marginal-marine interval, including Facies 6 (high-angle planar cross-stratified sandstone), Facies 7 (flaser-bedded sandstone), Facies 8A/B/C (wavy-bedded sandstone), Facies 9 (thinly interlaminated sandstone and siltstone), Facies 10 (very thinly interlaminated mudstone and sandstone); and an upper open-marine interval, including Facies 11 (coquina), Facies 3B (interbedded highly bioturbated siltstone and micro-hummocky cross-stratified sandstone), and Facies 1 (black shale). Eight of the facies mentioned above are identified in the more proximal location of southeastern corner of Saskatchewan, and the facies comparison between these two areas is provided in Table 2.

Table 3 shows the facies identified in this research area with corresponding porosity and permeability measured in southeastern Saskatchewan by Angulo and Buatois (2011). As we can see from Table 3, lithology strongly controls the porosity and permeability, since Facies 2B, 3, 6 and 7 which are dominated by siltstone or interlaminated siltstone and sandstone tend to have lower porosity and permeability (from corresponding facies in southeastern Saskatchewan) than those dominated by sandstone, namely Facies 1, 2A and 5. In addition, the grazing trails of *Nereites missouriensis* and feeding structures of *Phycosiphon incertum* in Facies 5 probably have an impact on increasing the permeability, as they generally consists of horizontal tunnels with a core filled with clay and envelope zone characterized by cleanser sandstone, which may promotes the gas and light oil transmissivity (Angulo and Buatois, 2011). However, what need to be mentioned is that the petrophysical characters can vary from place to place, and those measured in southeastern Saskatchewan only provide a reference for the porosity and permeability of

southeastern corner of Saskatchewan. For example, unit B2 are essentially calcite-cemented in southeastern Saskatchewan, but in the southeastern corner of Saskatchewan, particularly the Rocanville oil field, the calcite cements tend to present in the form of individual cemented blebs instead of pervasive cementation (Figure 28), which is explained as insufficient calcium remained within the formation water while reaching the Rocanville area (Kohlruss and Nickel, 2009). Where without these calcite-cemented blebs, the Unit B2 in the Rocanville area displays excellent reservoir qualities revealed by thin-section study (Kohlruss and Nickel, 2009), and light-oil staining is observed from some cores (Figure 28).

This Thesis Southeastern Corner of Saskatchewan		Angulo and Buatois (2011) Southeastern Saskatchewan		
Facies	Depositional Environment	Facies	Porosity	Permeability
1	Barrier Bar	6	8.6%	0.27mD
2A	Bay Margin	8A	7.9%	0.09mD
2B	Bay Margin	9	5.2%	0.04mD
3	Distal Bay	10	4.9%	0.07mD
4	Transgressive Lag	11		
5	Offshore Transition	4	10.6%	0.09mD
6	Upper Offshore	3B	5.5%	0.03mD
7	Lower Offshore	2	4.1%	0.02mD
8	Shelf	1		

Table 3- Facies identified in the southeastern corner of Saskatchewan with corresponding porosity and permeability measured in southeastern Saskatchewan (Angulo and Buatois, 2011).

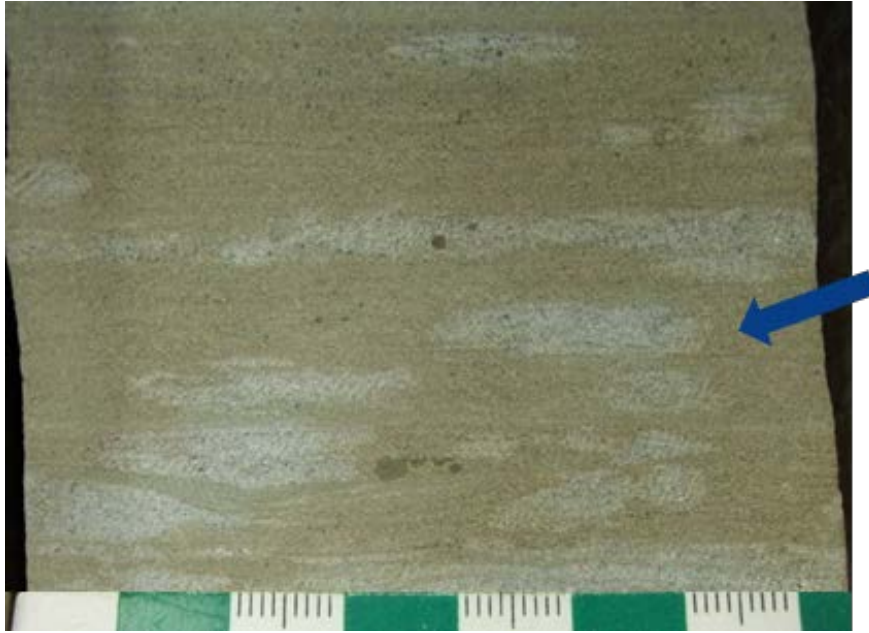


Figure 28- Core photo of Unit B2 from well: 08-34-015-31W1 (depth: 675.18m) in the Rocanville oil field. The blue arrow points to an example of calcite-cemented blebs.

Rocks of Devonian-Carboniferous age are highly attractive for academics and industry, as being active hydrocarbon producing units in North America. In addition to the Bakken Formation, the Middle Devonian Marcellus Shale of the Appalachian Basin is now an emerging shale gas play (Lash and Engelder, 2011). Throughout much of the basin, the Marcellus Shale consists of a middle member of limestone/shale/sandstone, sandwiched by two black shale members (de Witt et al., 1909). The most recent work by Emmanuel (2013) suggests that deposition of the Marcellus Shale took place in a bathymetrically subdued setting analogue to present-day continental shelves, which is probably similar to the Bakken depositional setting, but with a more complicated overprint of subsidence/uplift events, salinity variation, seasonal variations of nutrient and clastic influx rates. Bioturbation in the Marcellus Shale is quite sparse, which is alike to the lower and upper shale of the Bakken Formation. Similar to the tight oil and gas production of the Bakken Formation, the gas production from Marcellus Shale also requires horizontal drilling and hydraulic fracturing.

The Mississippian (Lower Carboniferous) Fayetteville shale is another

unconventional reservoir in the United States, which is a black, organic-rich rock in the Arkoma basin that underlies much of northern Arkansas (Handford, 1986). Due to the low permeability and low porosity nature of black shale, horizontal drilling and hydraulic fracturing are also adopted in the development of the Fayetteville shale reservoir for more efficient gas production (Arthur et al., 2008). The Fayetteville shale, together with the conformably overlying Pitkin limestone, are interpreted to be deposited in a shoaling-upward succession consisting of shelf, storm-dominated offshore and shoreface environments (Handford, 1986). This is probably a carbonate shallow-marine analogue for the Bakken deposition.

The Upper Devonian Woodford shale is also a prolific unconventional gas reservoir, which is preserved across the Arkoma Basin of southeast Oklahoma (Brown, 2008) and Permian Basin of west Texas (Hemmesch, 2014). The strata are dominated by unbioturbated organic-rich mudstone overlain by a bioturbated organic-poor mudstone (Hemmesch, 2014). The organic-rich mudstone is interpreted as having been deposited in a restricted and localized anoxic marine environment which was conducive to preservation of organic matter (Slatt et al., 2015). The organic-poor mudstone is highly bioturbated, and primary sedimentary structures are almost invisible. The ichnofauna is dominated by simple small burrows and the possible presence of rare large *Teichichnus*, suggesting a fully oxygenated to shelf environment (Hemmesch, 2014). The depositional environment is similar to that of the Bakken, and the dominance of simple small burrows is probably associated with the Late Devonian mass extinction or some stressful environmental parameters.

9. CONCLUSIONS

An integrated sedimentology, ichnology and sequence stratigraphy study of the Upper Devonian-Lower Mississippian Bakken Formation in the southeastern corner of Saskatchewan has been undertaken. Based on detailed sedimentologic and ichnologic analysis of 40 cores, eight facies (one of them subdivided into two subfacies) were identified: Facies 1 (planar cross-stratified fine-grained sandstone); Facies 2A (wavy- to flaser-bedded very fine-grained sandstone); Facies 2B (thinly parallel-laminated very fine-grained sandstone and siltstone); Facies 3 (parallel-laminated very fine-grained sandstone and muddy siltstone); Facies 4 (sandy siltstone); Facies 5 (highly bioturbated interbedded very fine-grained sandstone and siltstone); Facies 6 (interbedded highly bioturbated sandy siltstone and micro-hummocky cross-stratified very fine-grained sandstone); Facies 7 (highly bioturbated siltstone); and Facies 8 (black shale). Facies 1 to 3 are grouped into a brackish-water marginal-marine facies association, which records deposition in an embayment with limited or intermittent connection to the open sea (subunits B2 and B3 of the middle Bakken member); Facies 4 to 8 (upper member) are grouped into an open-marine facies association, which represents sedimentation in a low-energy wave-influenced open marine (unit C of the middle Bakken member and upper Bakken shale member).

The open-marine facies association is highly bioturbated and displays moderate ichnodiversity, illustrating the distal *Cruziana* Ichnofacies. The marginal-marine facies association shows low intensities of bioturbation and is characterized by low ichnodiversity, representing the depauperate *Cruziana* Ichnofacies.

Isochore maps show that both open-marine and marginal-marine deposits are widespread in the study area. For the open-marine facies, the more distal deposits tend to be thicker in the west, whereas the more proximal deposits tend to be thicker in the east, indicating a N-S trending paleo-shoreline. For the brackish-water marginal-marine facies, the bay-margin deposits tend to be thicker in the west,

whereas the distal-bay deposits tend to be thicker in the east, which is probably due to the irregular paleotopography inherited from the sea level fall.

Most commonly in this study area, the whole succession only consists of the middle marginal-marine deposits (subunit B2 and B3) overlain by the upper open-marine deposits (unit C and upper Bakken shale), representing a transgressive systems tract. The base of the marginal-marine interval is represented by a sequence boundary (coplanar surface or amalgamated sequence boundary and transgressive surface). When the lower Bakken shale is present, the whole succession consists of middle marginal-marine deposits (subunit B2 and B3) sandwiched by underlying (lower part of lower Bakken shale) and overlying (unit C and upper Bakken shale) open-marine deposits, representing two transgressive systems tracts separated by a coplanar surface. This surface is the base of the marginal-marine interval and has been identified in previous studies west-southwest of our study area (Angulo et al., 2008; Angulo and Buatois, 2012a), therefore assisting in high-resolution correlation of Bakken strata.

This thesis research provides a detailed description of sedimentary facies, trace fossils, depositional environments and sequence stratigraphy of the Bakken Formation in the southeastern corner of Saskatchewan. Together with previous work in southeastern Saskatchewan (Angulo and Buatois, 2012a), a more complete picture of late Devonian-lower Carboniferous sedimentary facies and stratal evolution in the Williston Basin is presented. Based on different facies identified, future work can be conducted by testing the porosity and permeability, building electrofacies model, and integrating with geomechanical and seismic data. It has an important impact on understanding the reservoir geometry and heterogeneity, and will assist in future oil exploration and production in this area.

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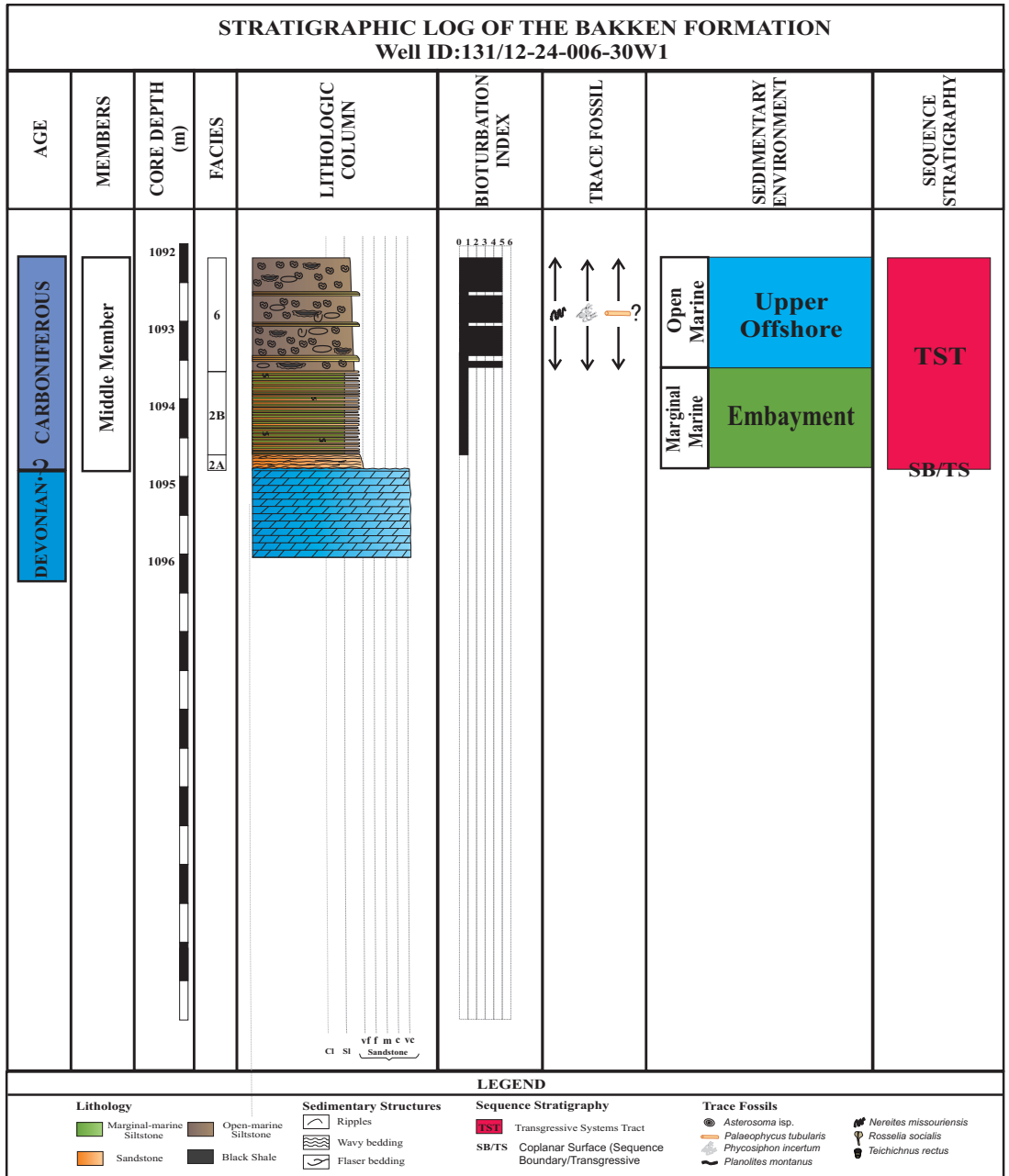
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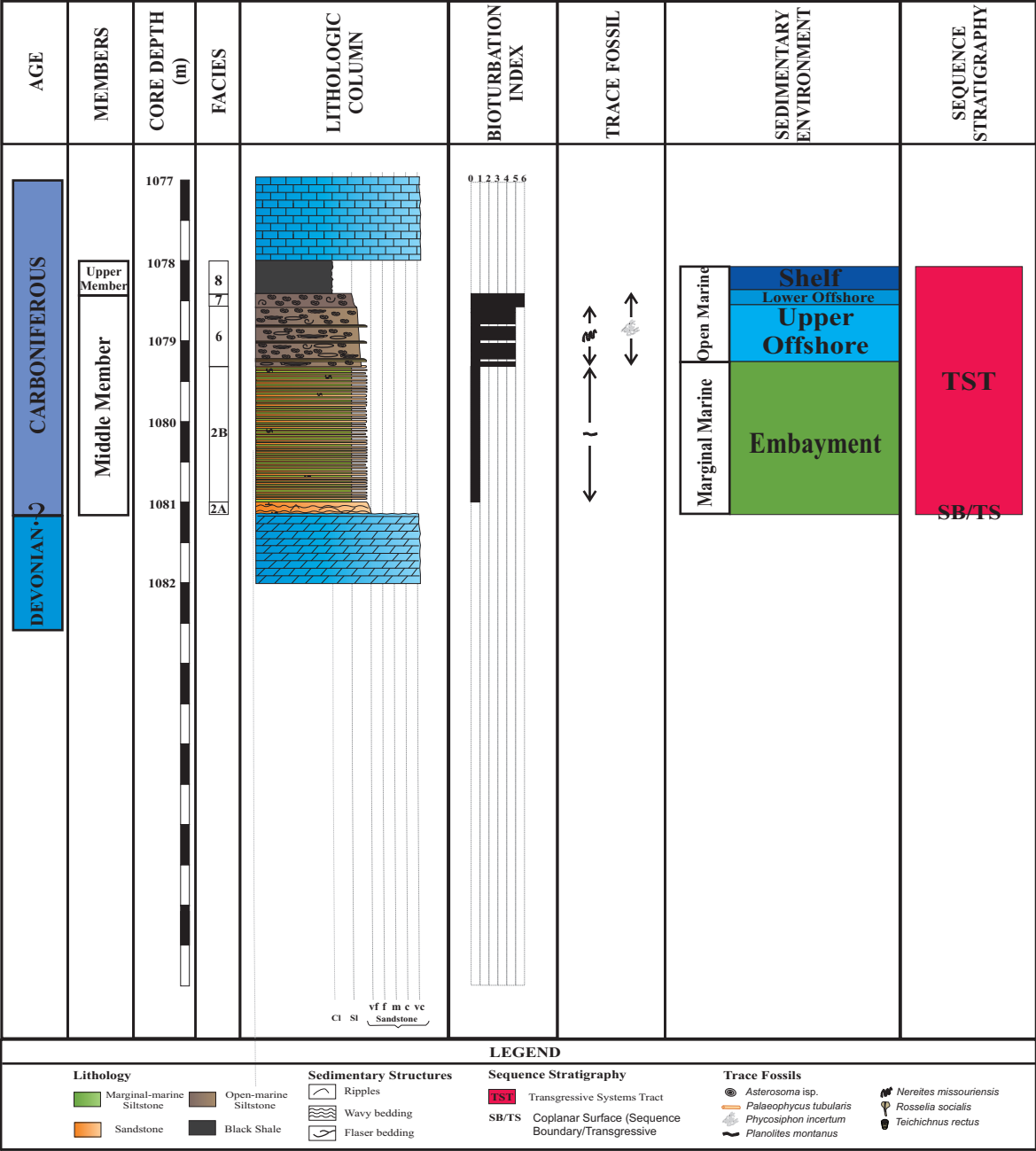
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APPENDI



STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

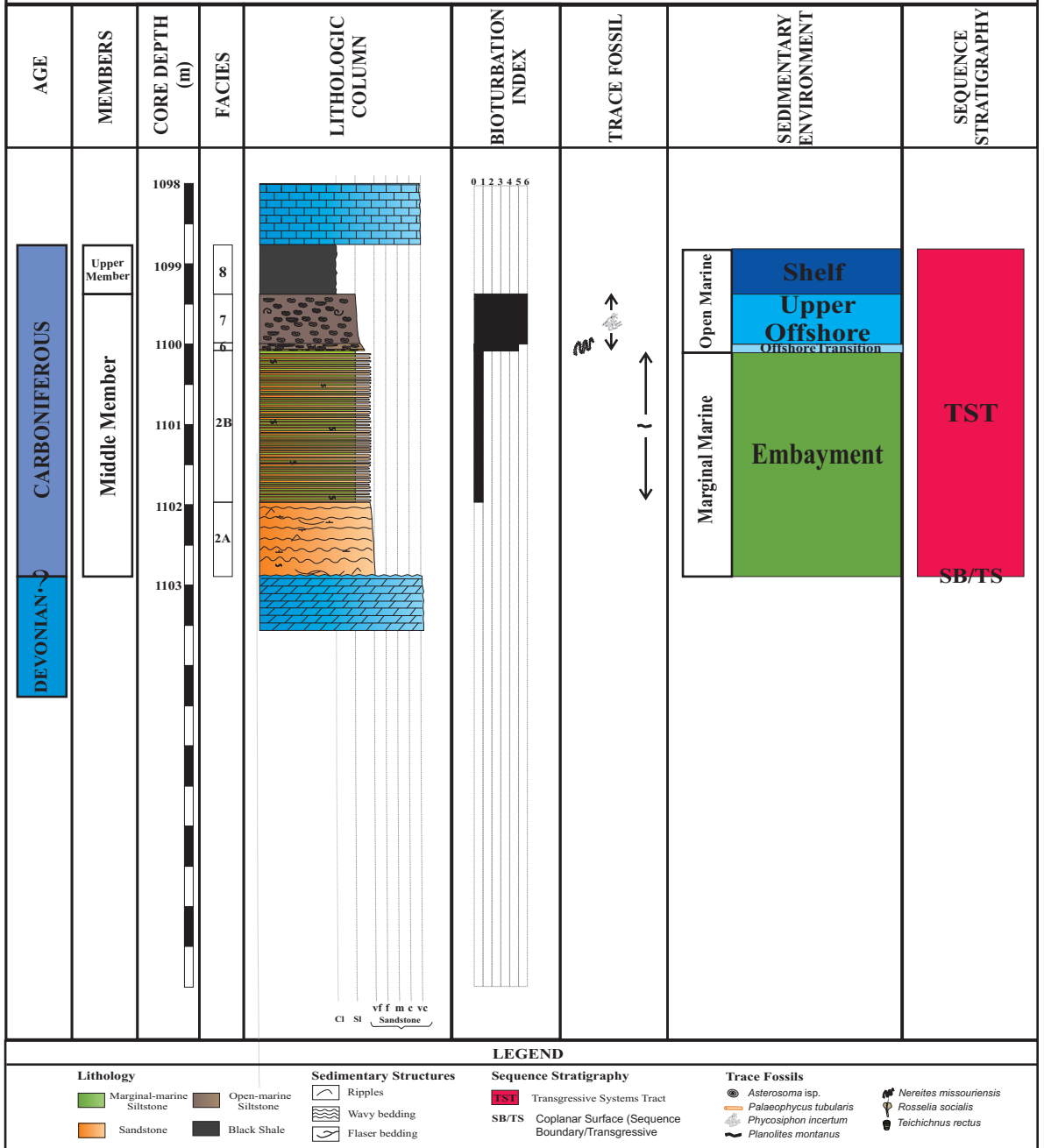
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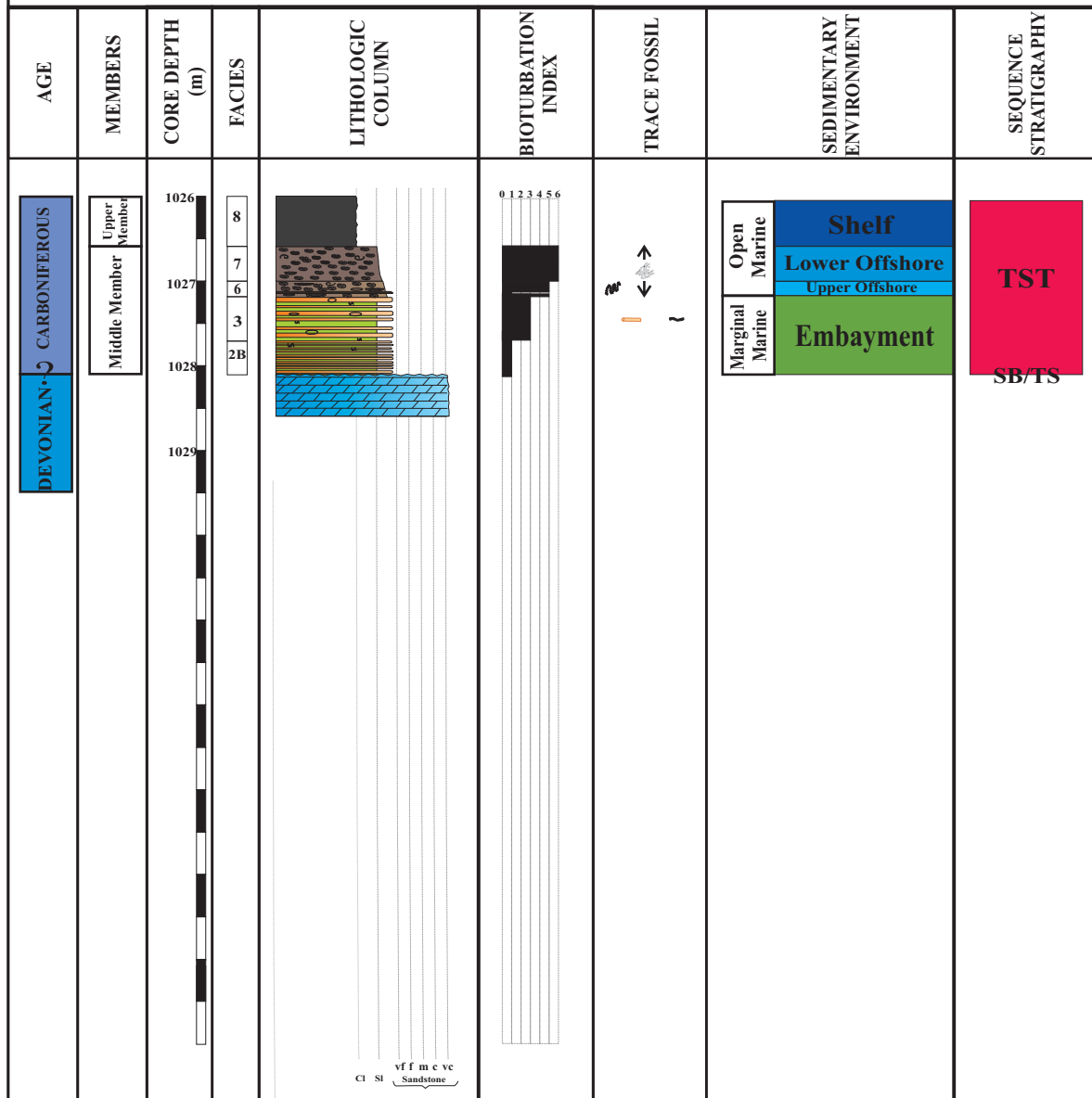
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STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:141/14-01-008-30W1



Cl Sl {vf f m c vc} Sandstone

LEGEND

Lithology

- Marginal-marine Siltstone
- Open-marine Siltstone
- Sandstone
- Black Shale

Sedimentary Structures

- Ripples
- Wavy bedding
- Flaser bedding

Sequence Stratigraphy

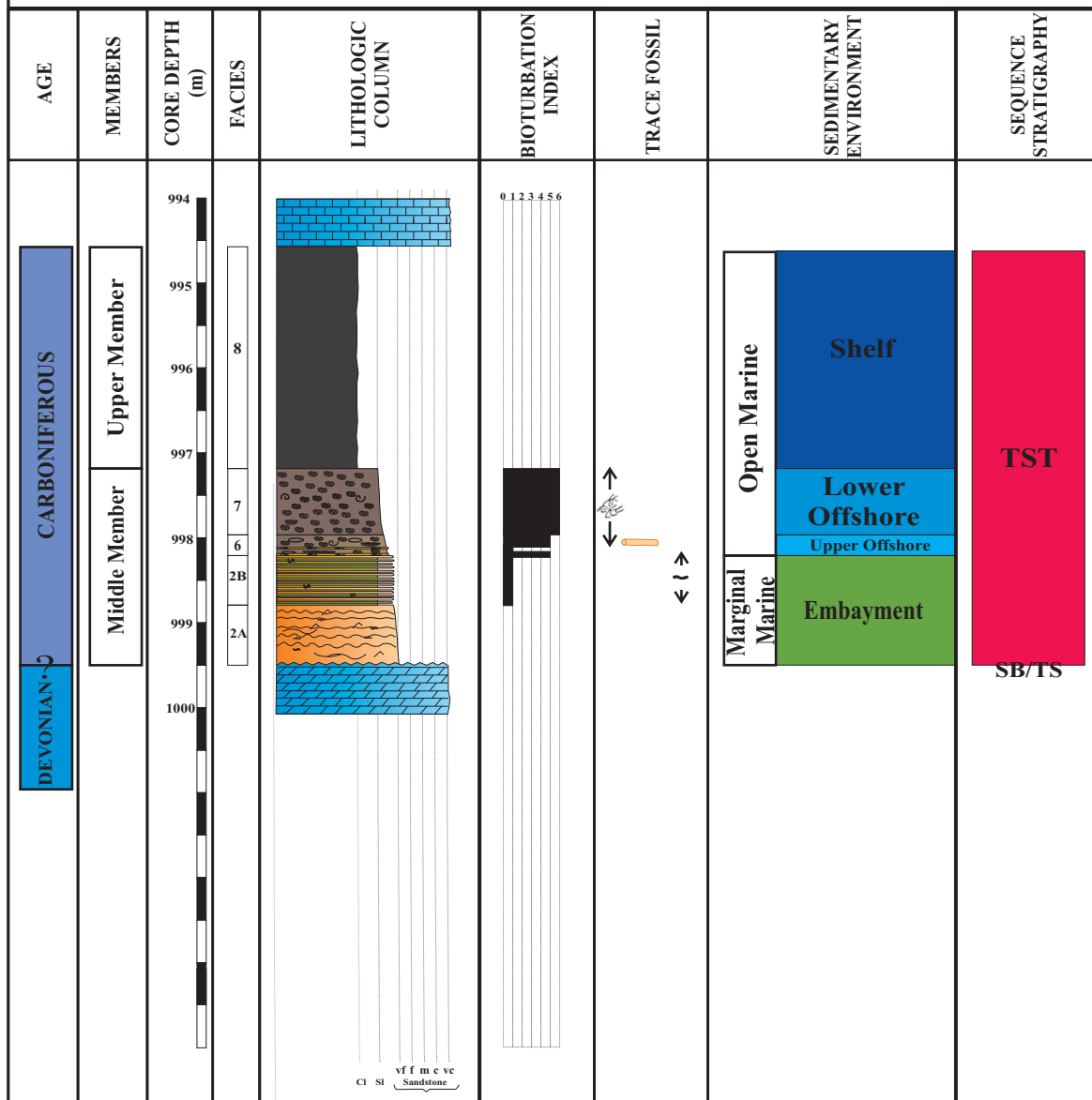
- TST Transgressive Systems Tract
- SB/TS Coplanar Surface (Sequence Boundary/Transgressive)

Trace Fossils

- Asterosoma isp.
- Palaeophycus tubularis
- Phycosiphon incertum
- Planolites montanus
- Nereites missouriensis
- Rosselia socialis
- Teichichnus rectus

STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:101/09-25-008-30W1



LEGEND

Lithology

- Marginal-marine Siltstone
- Open-marine Siltstone
- Sandstone
- Black Shale

Sedimentary Structures

- Ripples
- Wavy bedding
- Flaser bedding

Sequence Stratigraphy

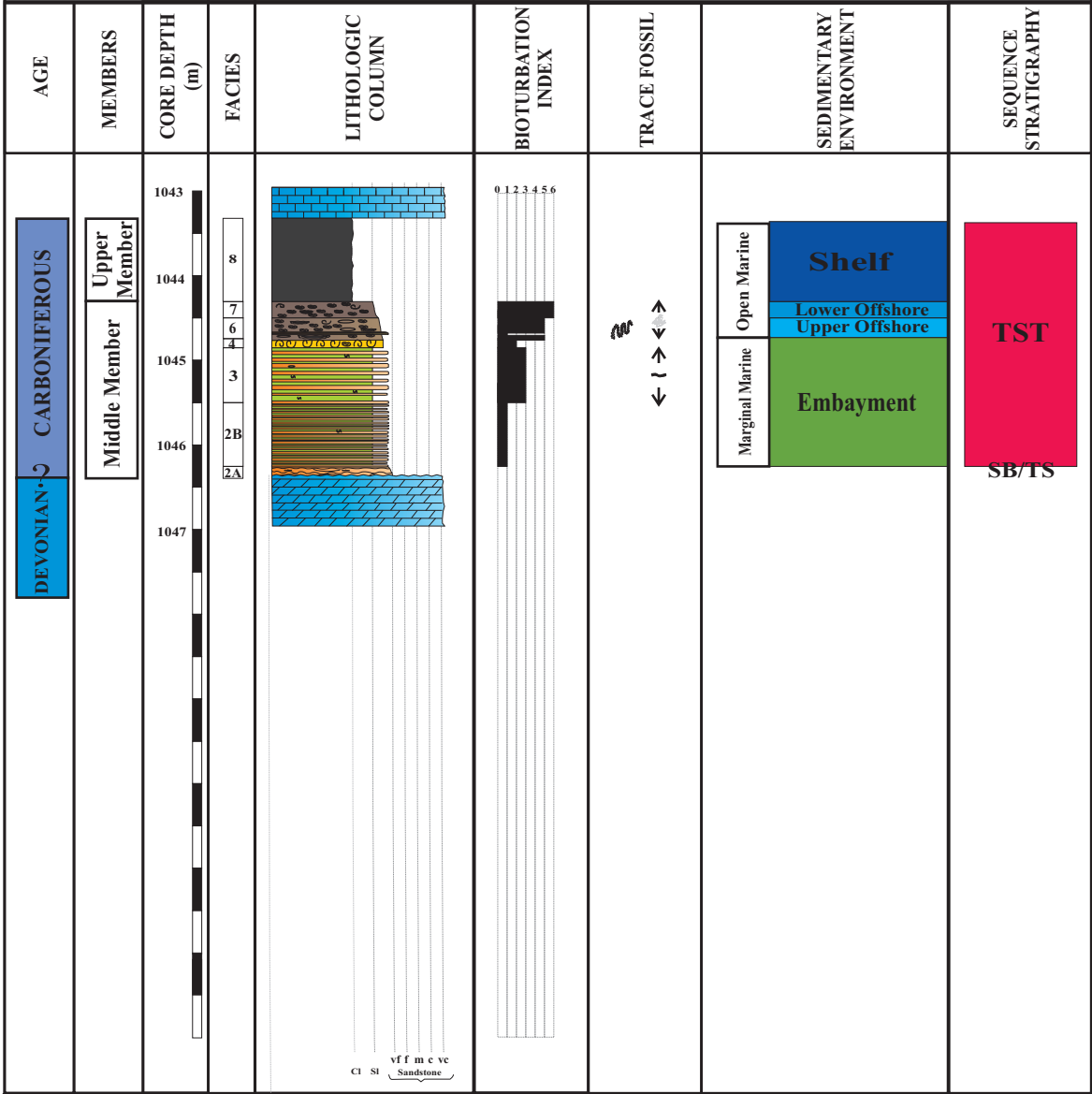
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- SB/TS Coplanar Surface (Sequence Boundary/Transgressive)

Trace Fossils

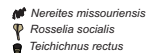
- Asterosoma isp.
- Palaeophycus tubularis
- Phycosiphon incertum
- Planolites mortuanus
- Nereites missouriensis
- Rosella socialis
- Teichichnus rectus

STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

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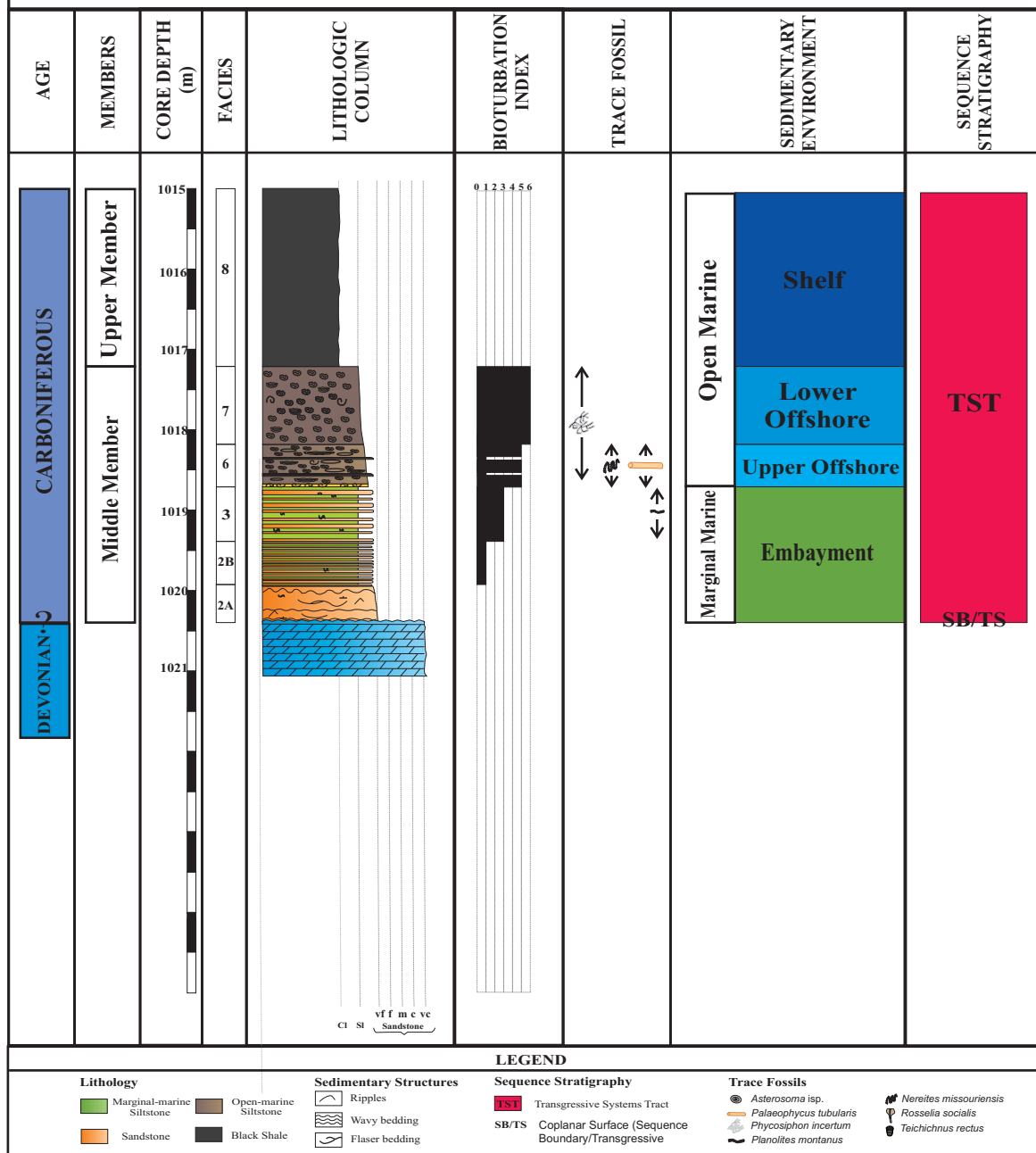


LEGEND



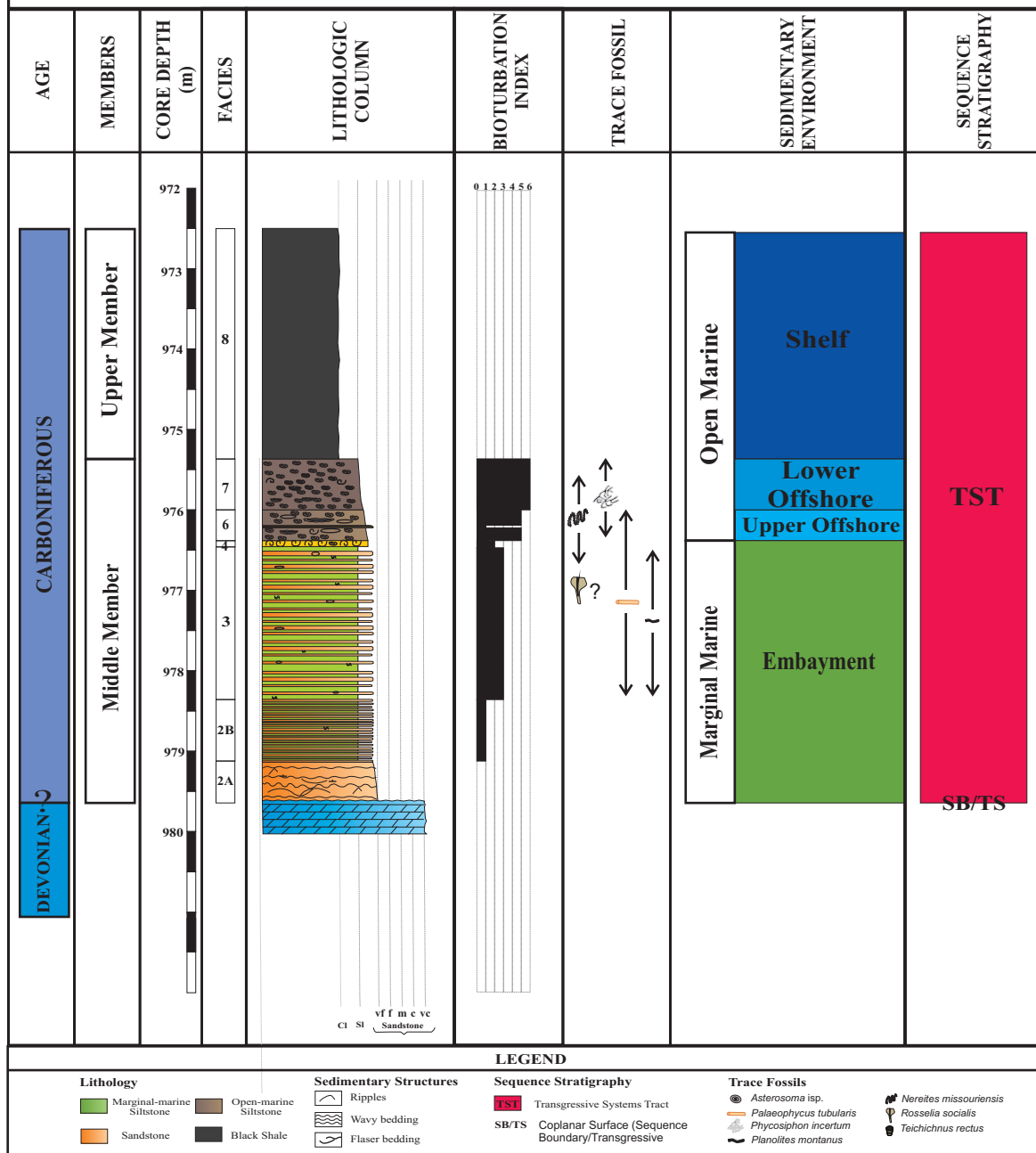
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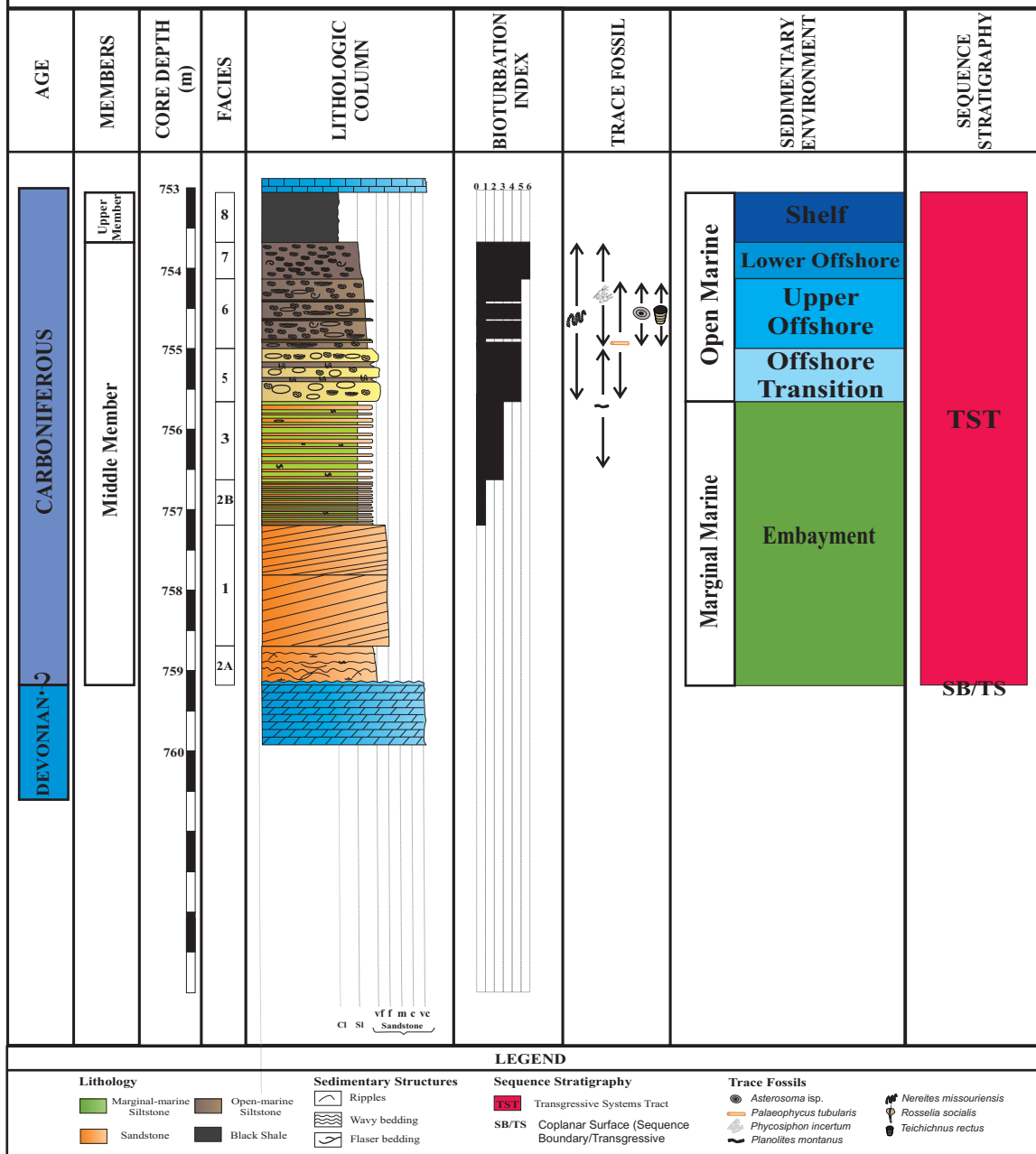


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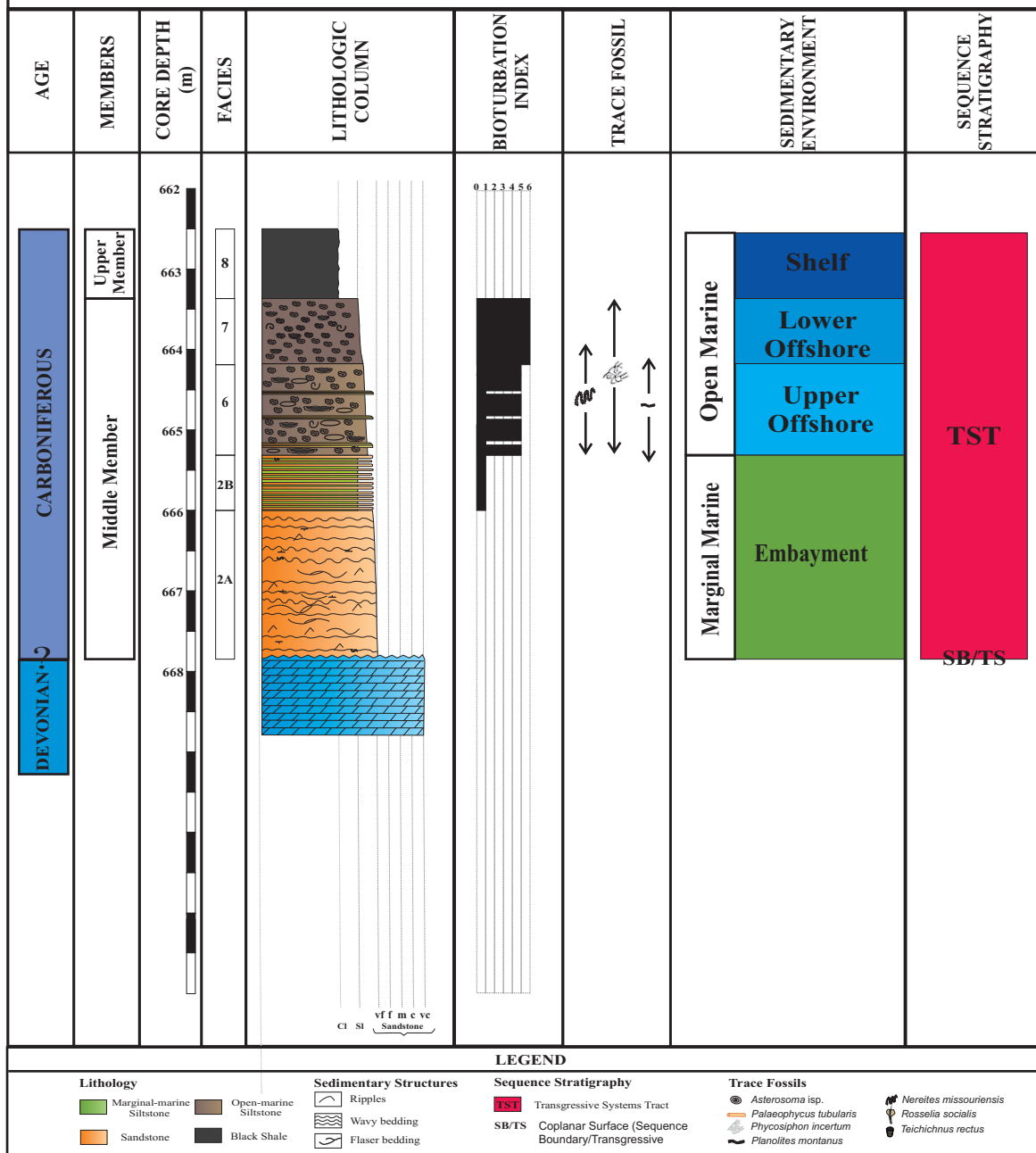


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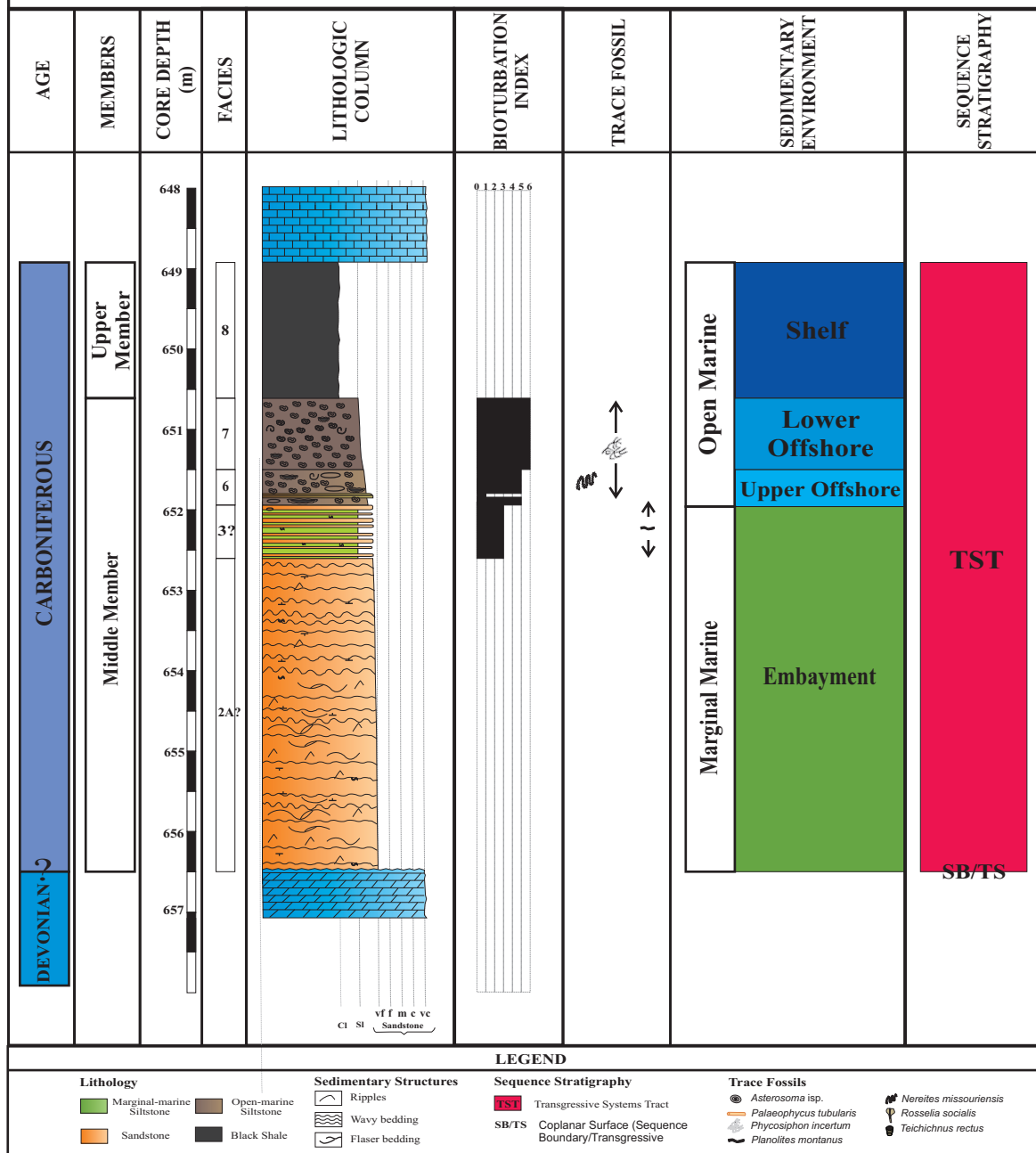
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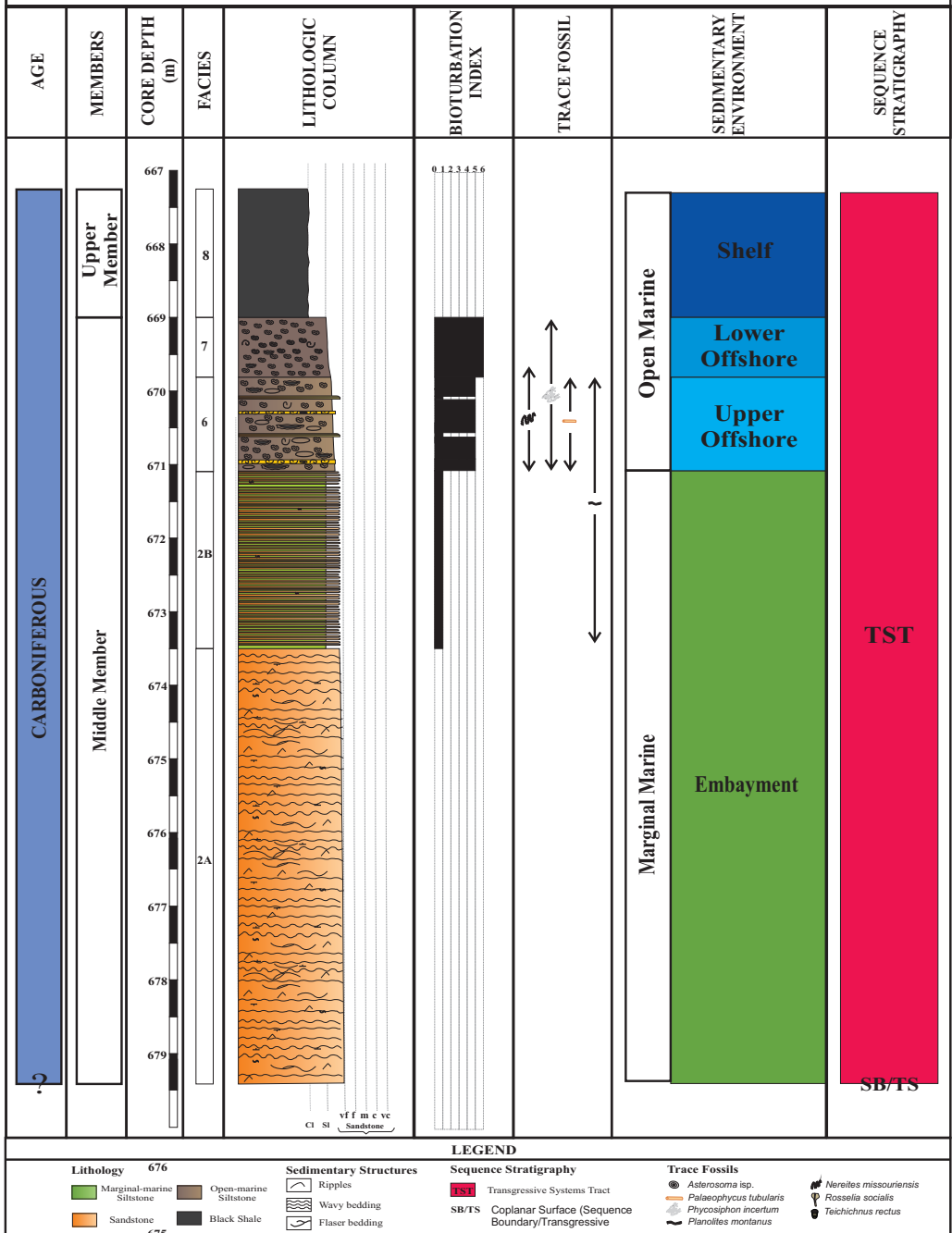


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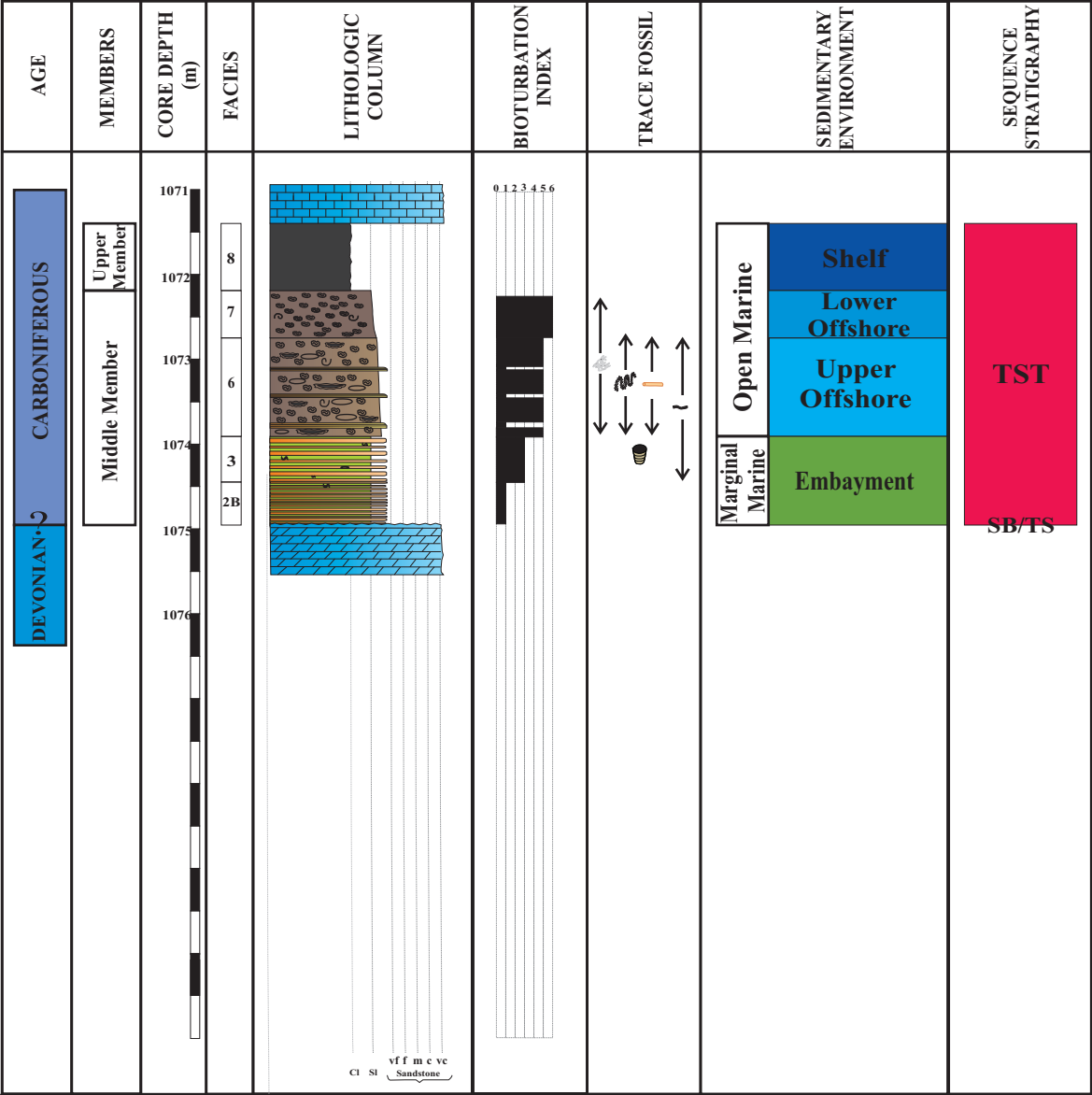
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STRATIGRAPHIC LOG OF THE BAKKEN FORMATION **Well ID:101/10-19-015-30W1**



STRATIGRAPHIC LOG OF THE BAKKEN FORMATION Well ID:131/16-17-009-31W1



Cl Sl v f f m c v c Sandstone

LEGEND

Lithology

- Marginal-marine Siltstone
- Open-marine Siltstone
- Sandstone
- Black Shale

Sedimentary Structures

- Ripples
- Wavy bedding
- Flaser bedding

Sequence Stratigraphy

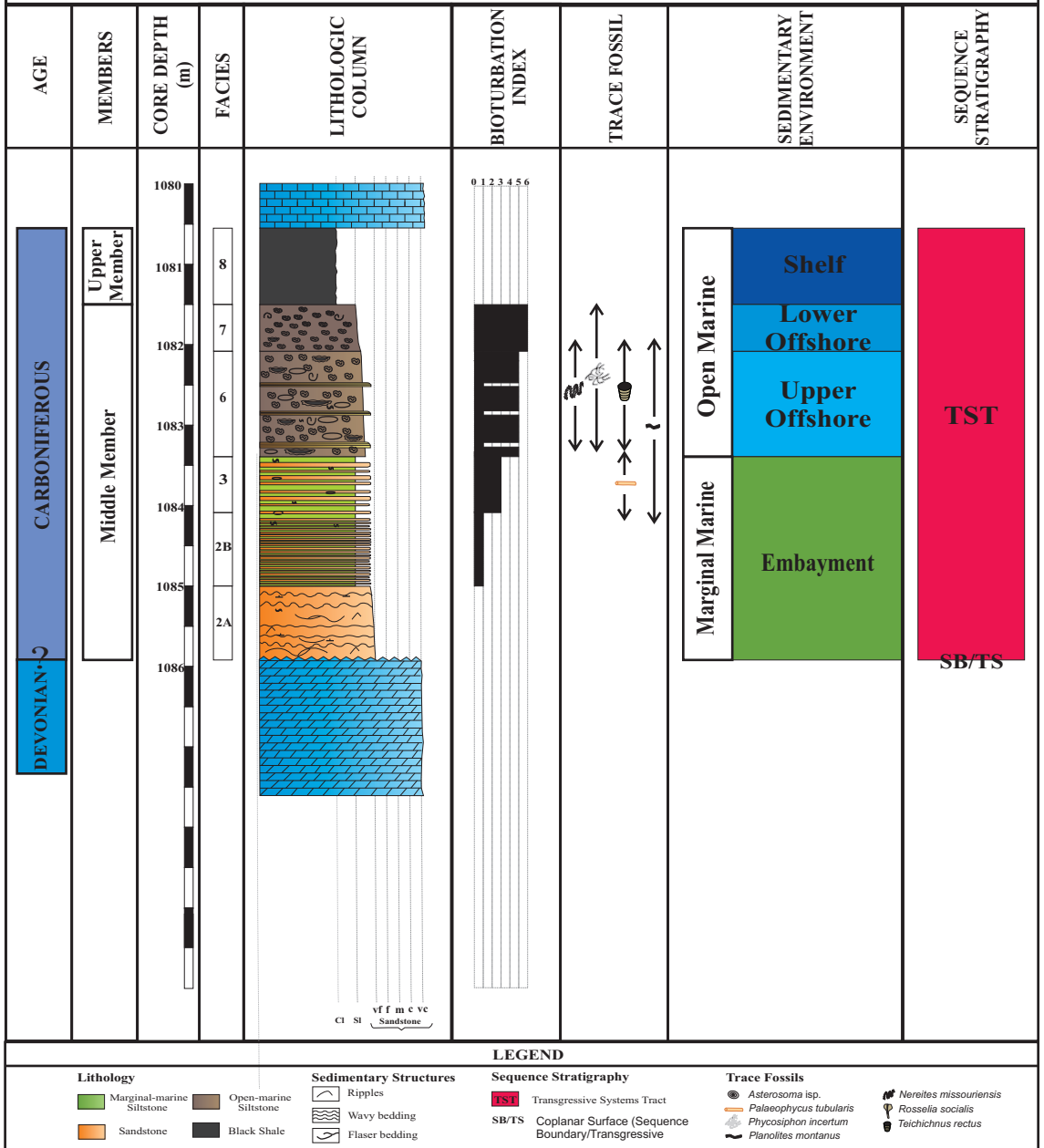
- TST Transgressive Systems Tract
- SB/TS Coplanar Surface (Sequence Boundary/Transgressive)

Trace Fossils

- Asterosoma isp.
- Palaeophycus tubularis
- Phycosiphon incertum
- Planolites montanus
- Nereites missouriensis
- Rosselia socialis
- Teichichnus rectus

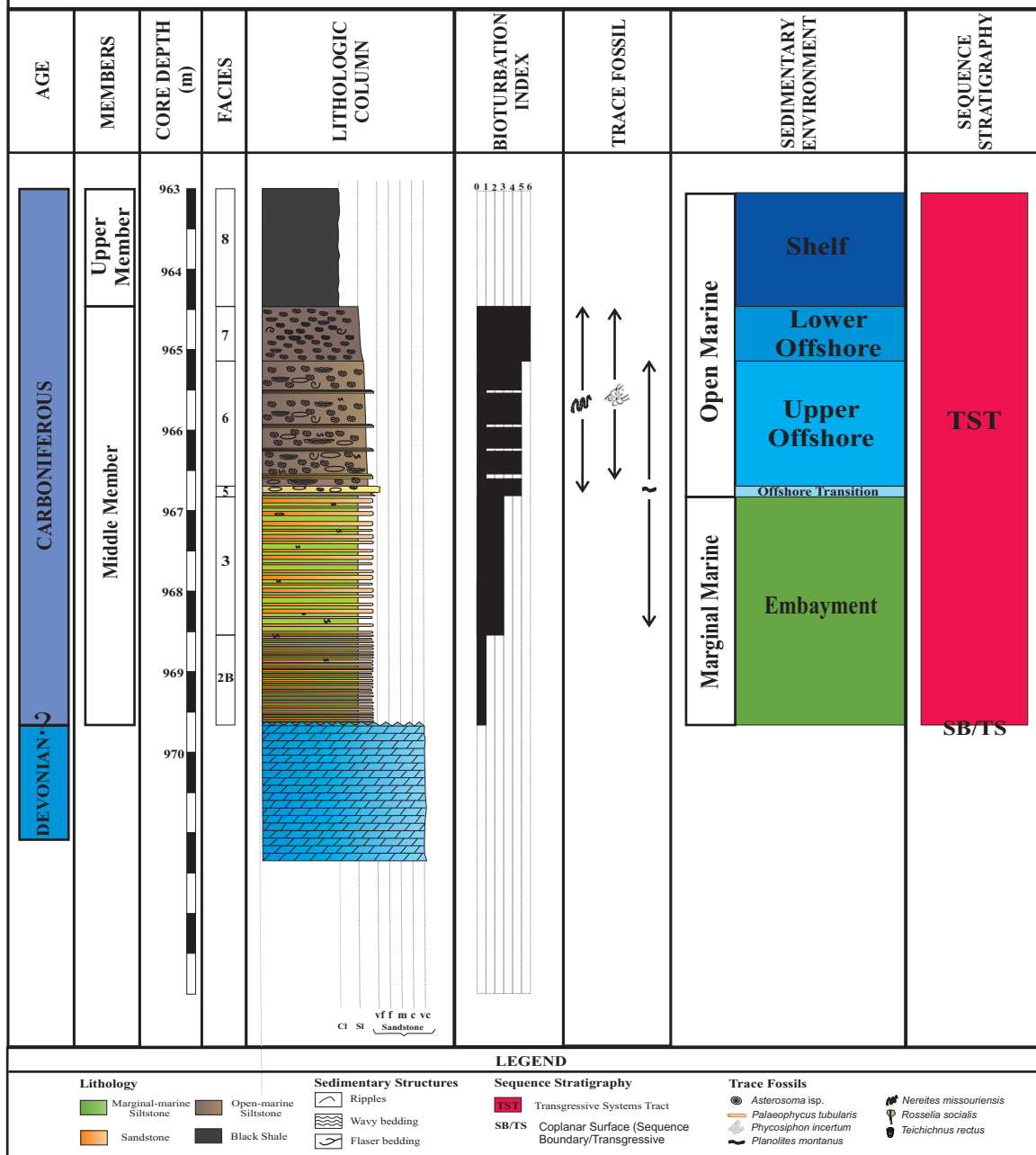
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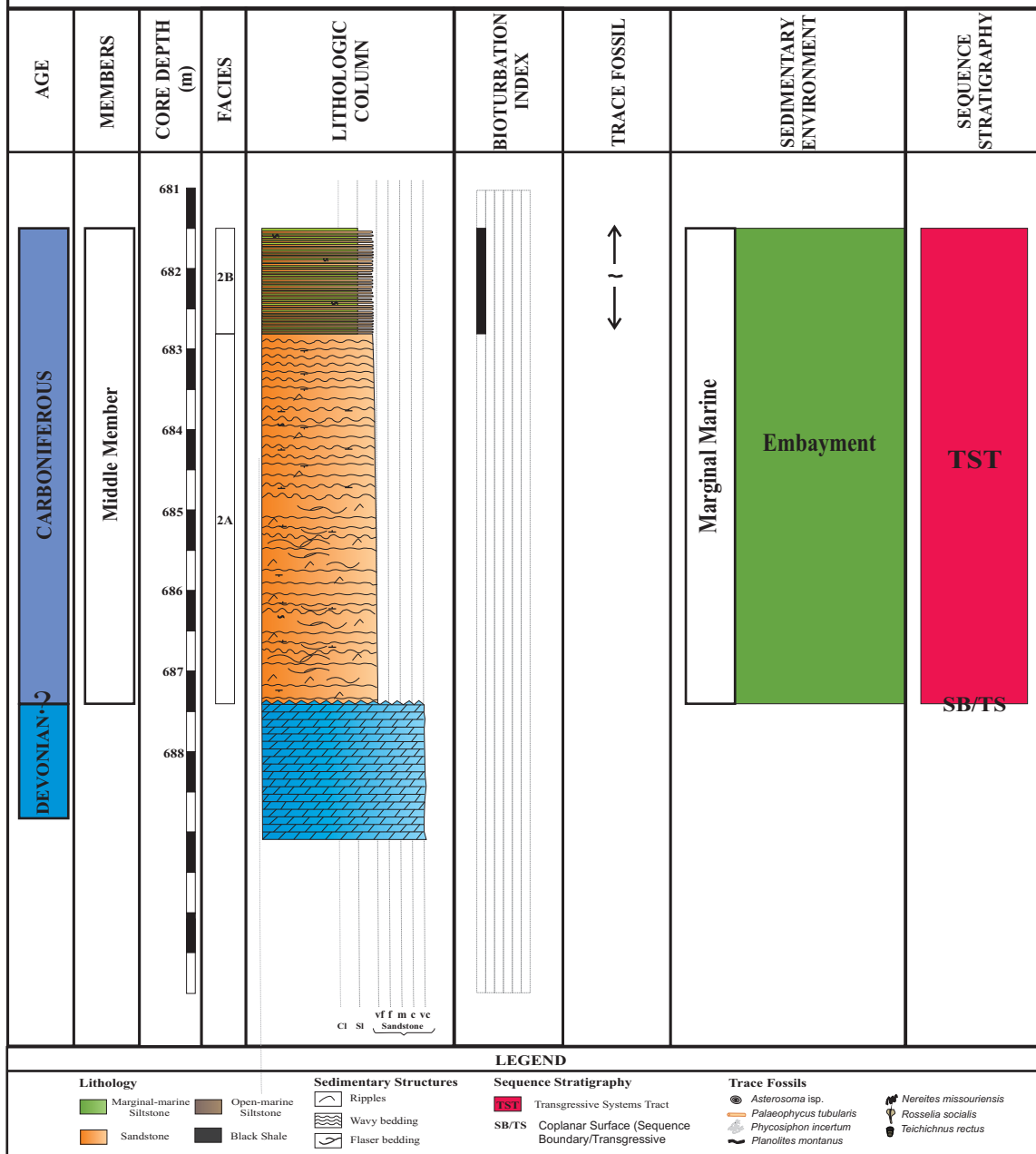
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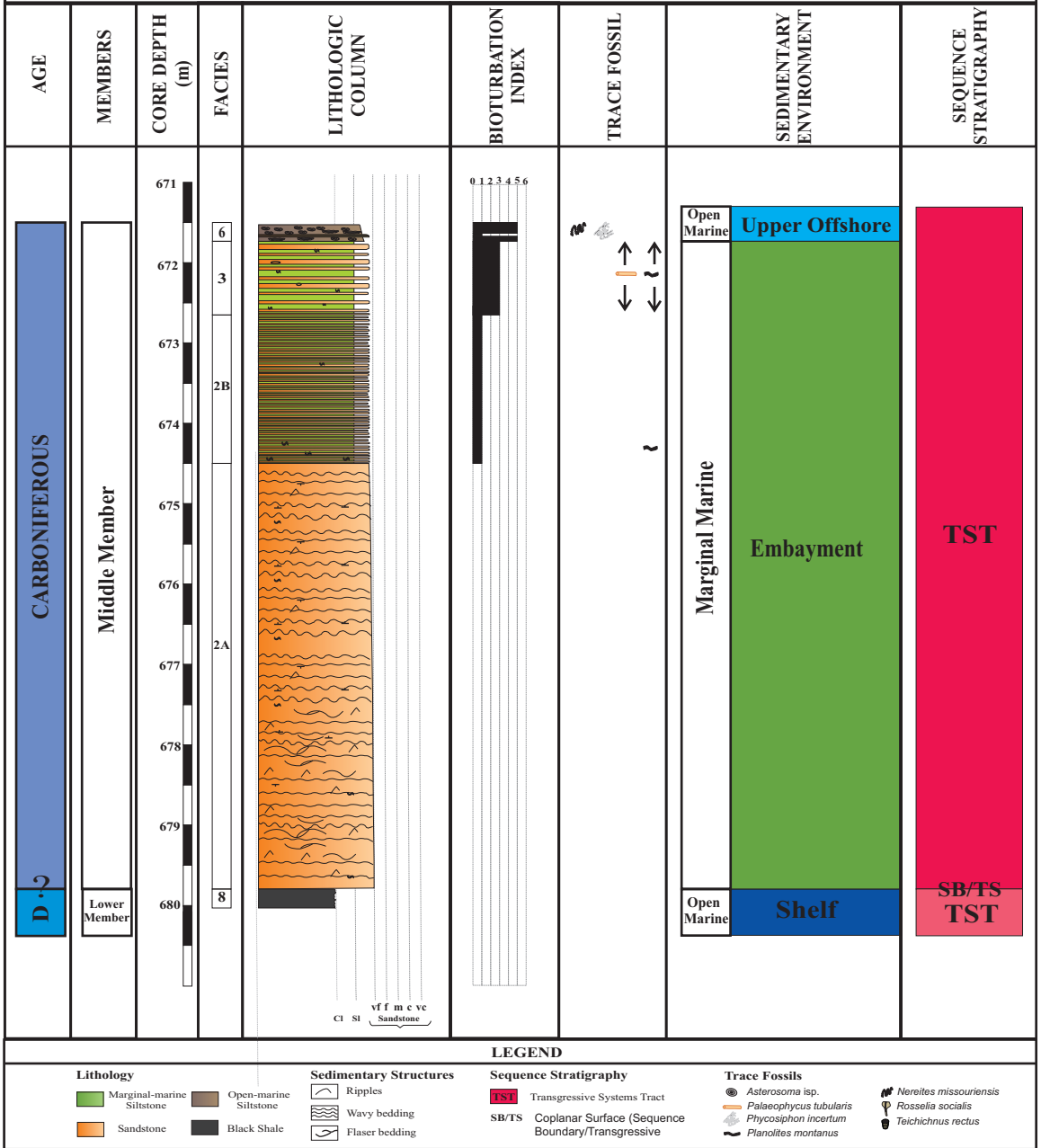
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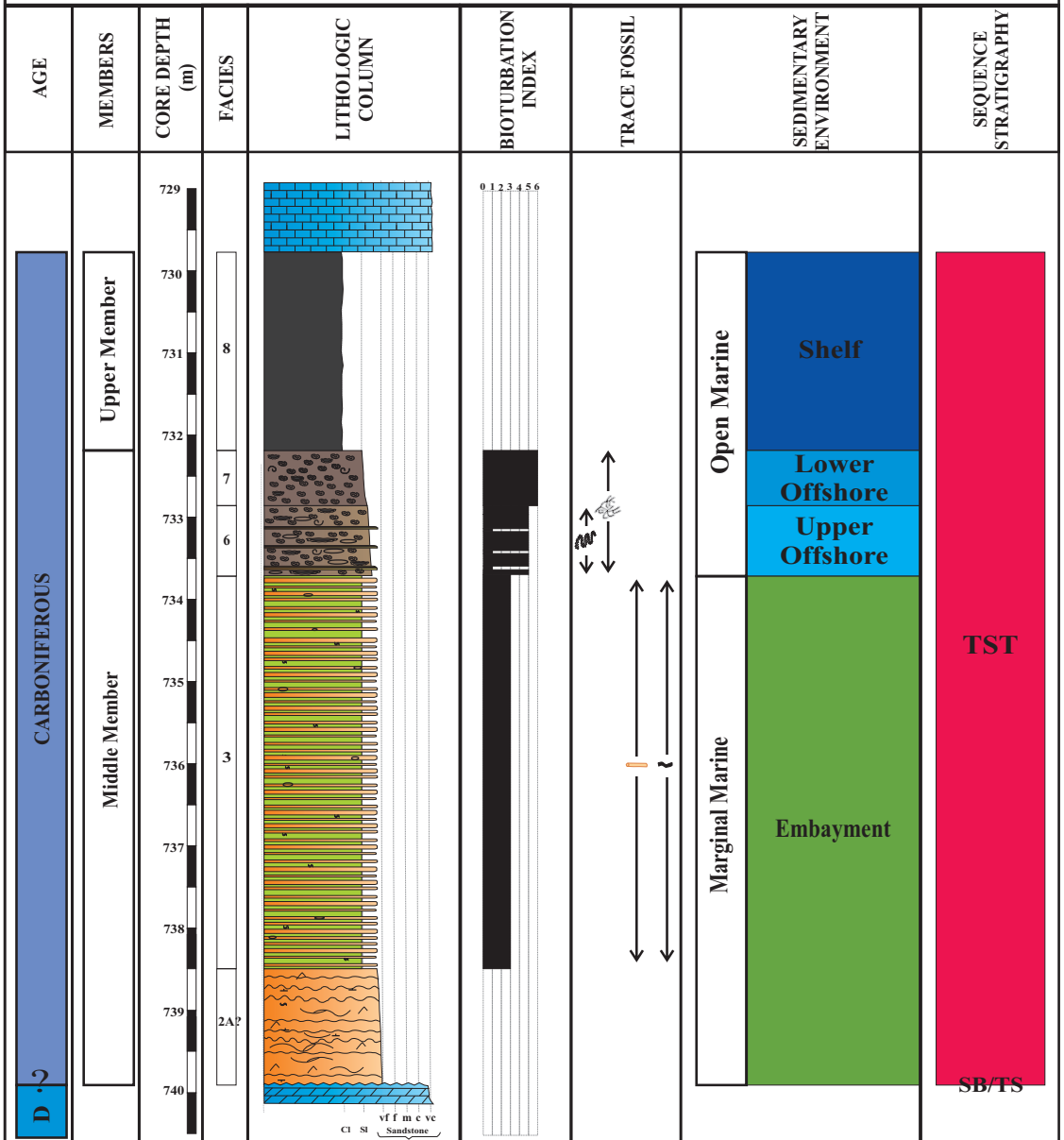
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STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:101/16-04-015-31W1



LEGEND

Lithology

- Marginal-marine Siltstone
- Open-marine Siltstone
- Sandstone
- Black Shale

Sedimentary Structures

- Ripples
- Wavy bedding
- Flaser bedding

Sequence Stratigraphy

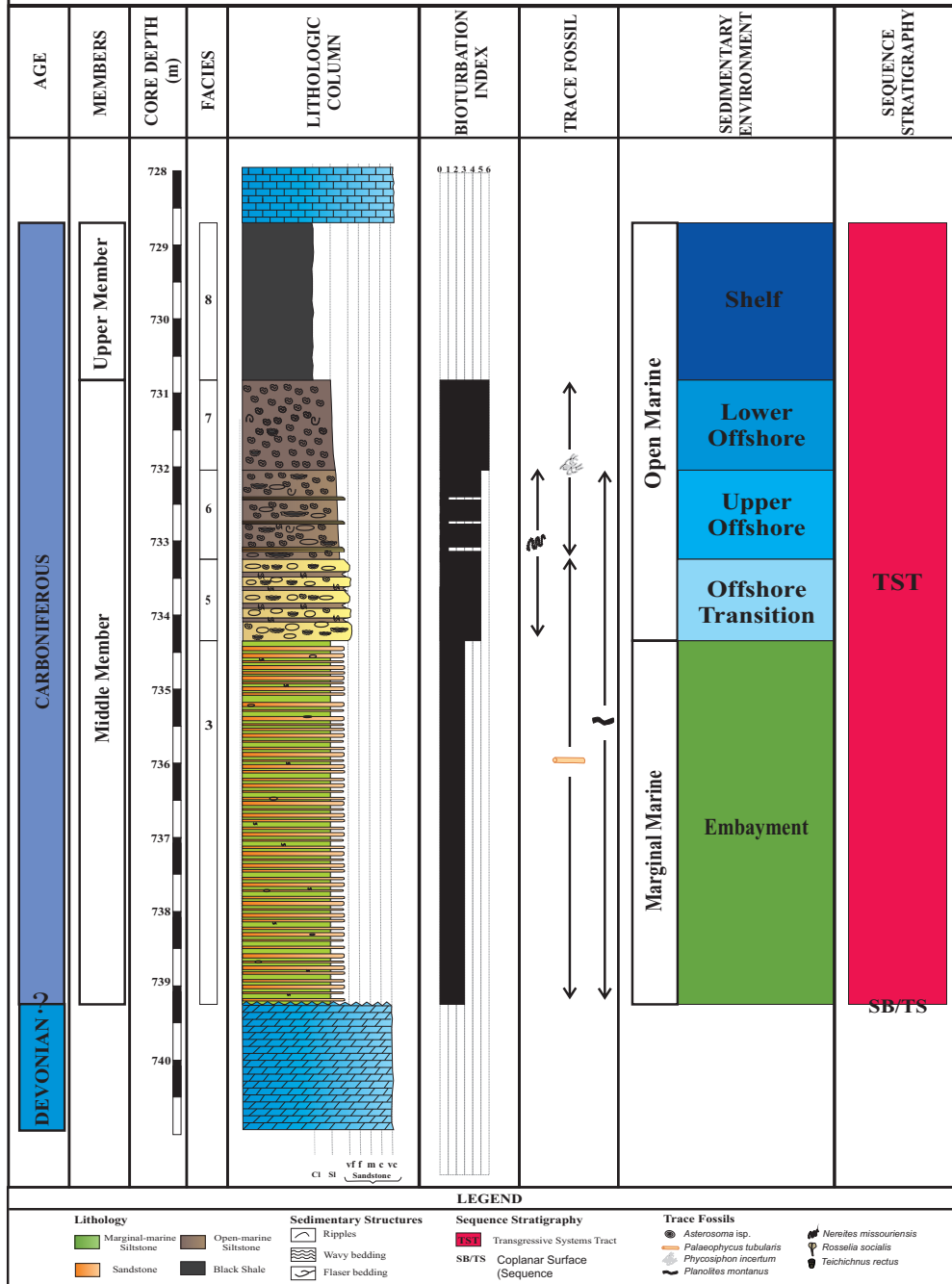
- TST Transgressive Systems Tract
- SB/TS Coplanar Surface (Sequence Boundary/Transgressive)

Trace Fossils

- Asterosoma isp.
- Palaeophycus tubularis
- Phycosiphon incertum
- Planolites montanus
- Nereites missouriensis
- Rosselia socialis
- Teichichnus rectus

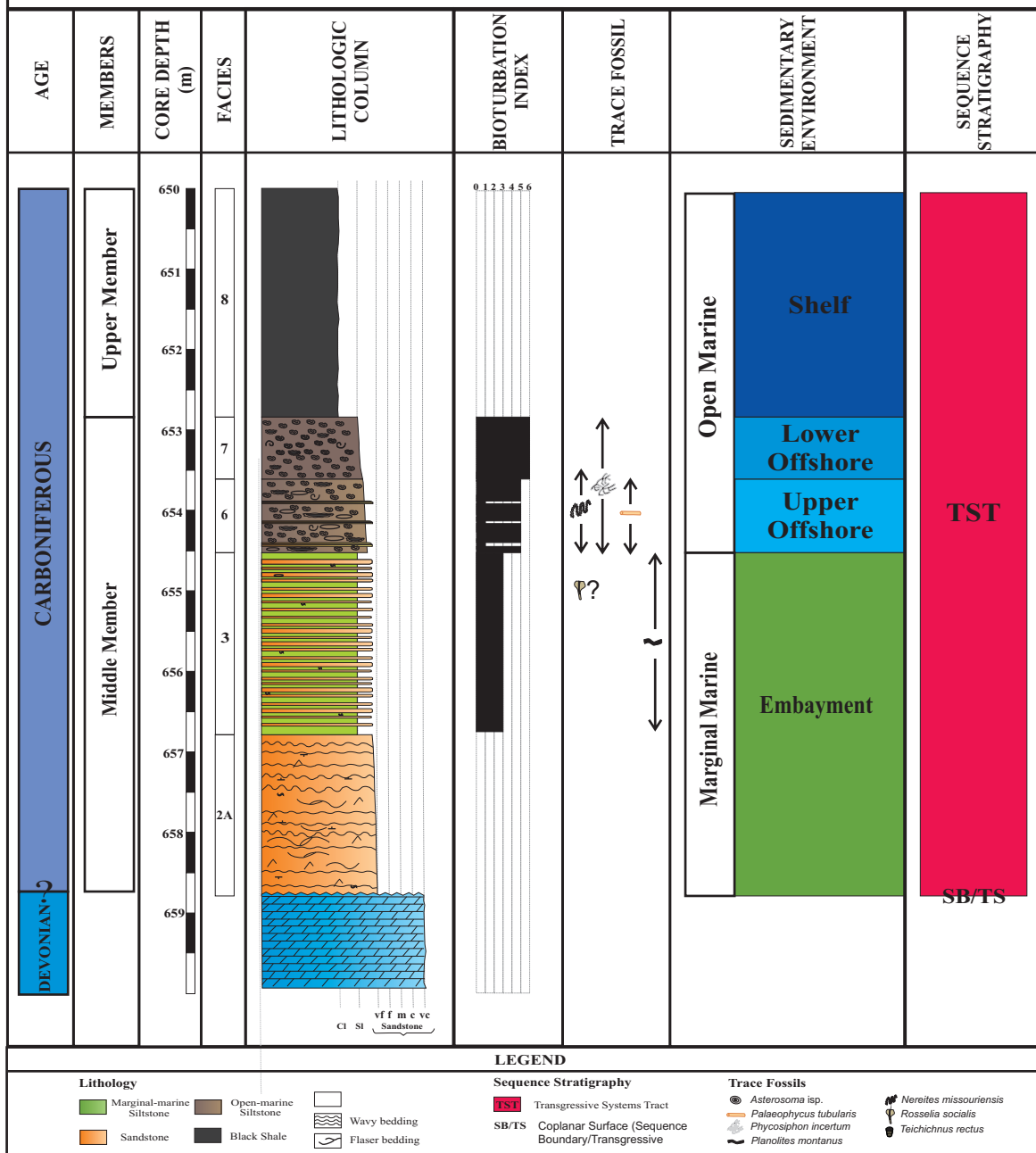
STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:101/01-09-015-31W1



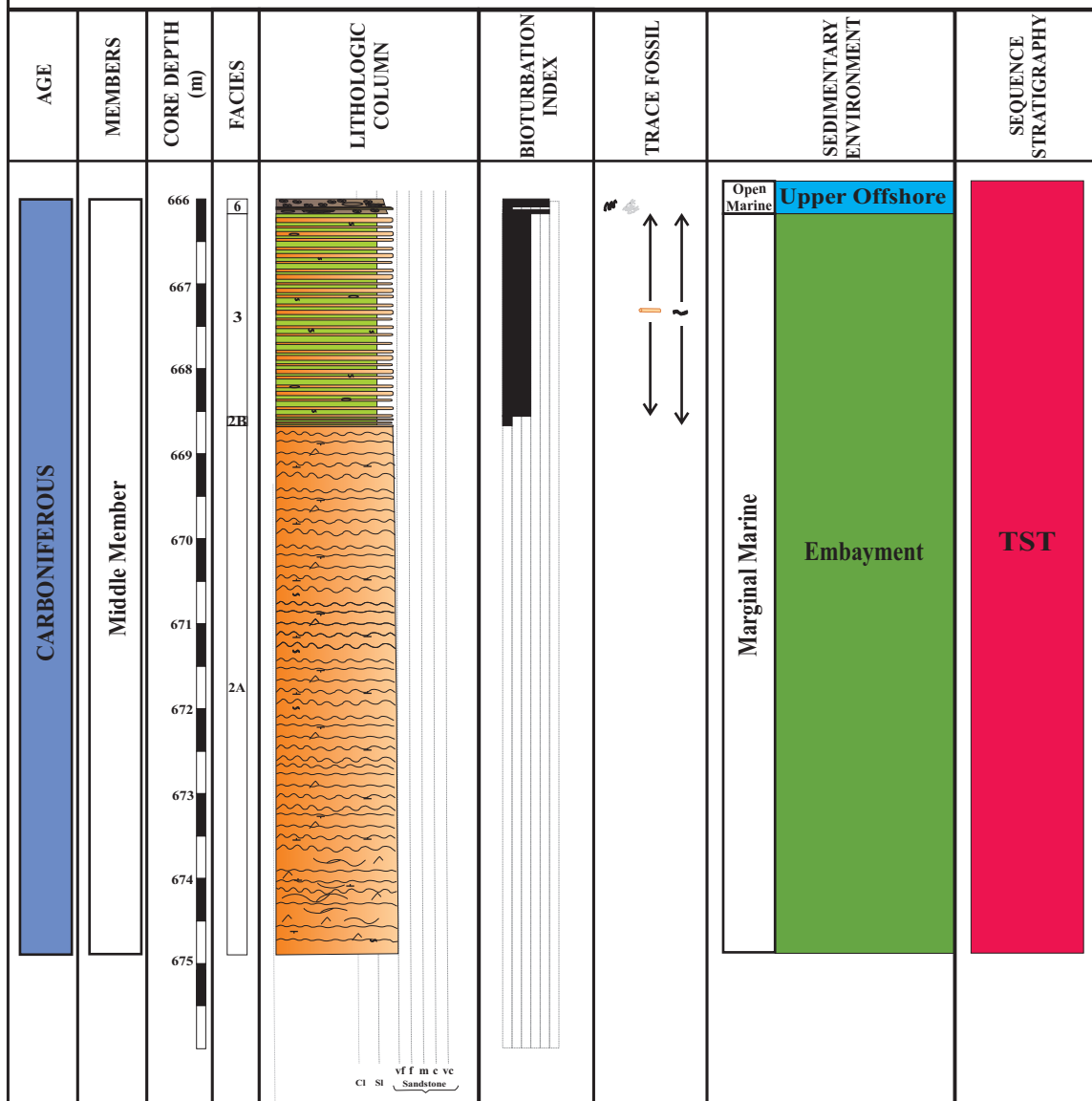
STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:101/10-12-016-31W1



STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:121/02-02-016-31W1



LEGEND

Lithology

- Marginal-marine Siltstone
- Open-marine Siltstone
- Sandstone
- Black Shale

Sedimentary Structures

- Ripples
- Wavy bedding
- Flaser bedding

Sequence Stratigraphy

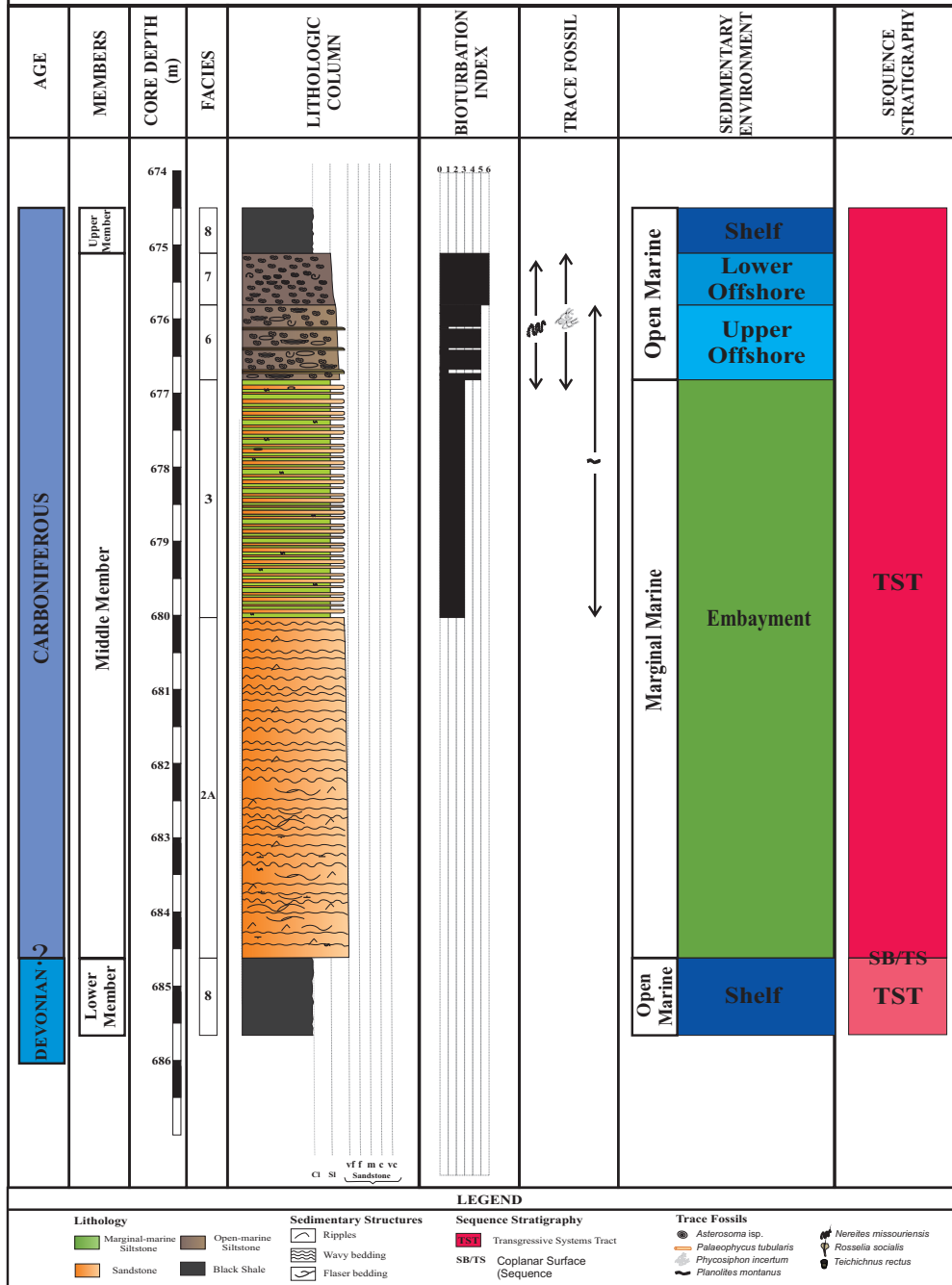
- Transgressive Systems Tract
- Coplanar Surface (Sequence Boundary/Transgressive

Trace Fossils

- Asterosoma* isp.
- Palaeophycus tubularis*
- Phycosiphon incertum*
- Planolites montanus*
- Nereites missouriensis*
- Rosselia socialis*
- Teichichnus rectus*

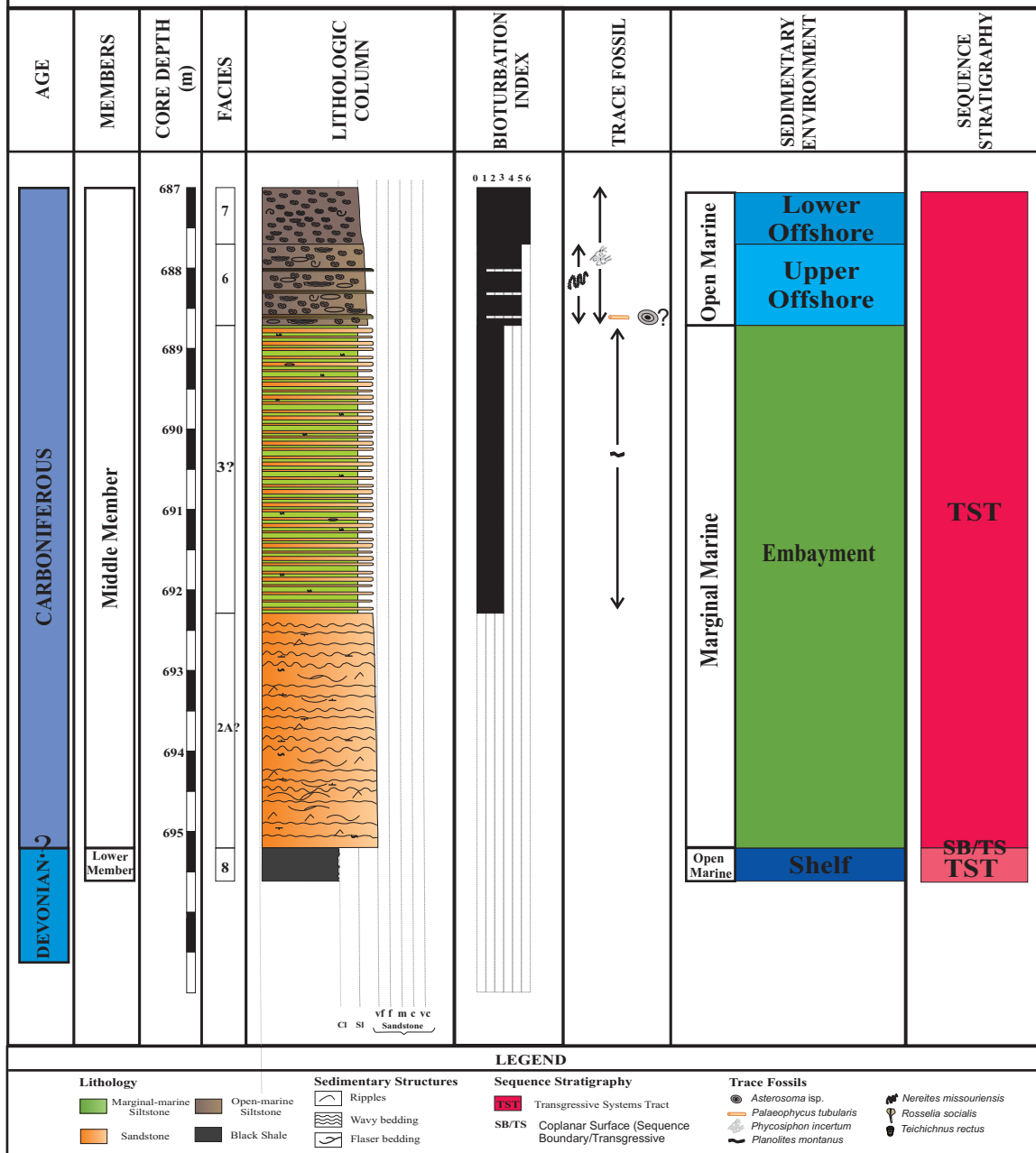
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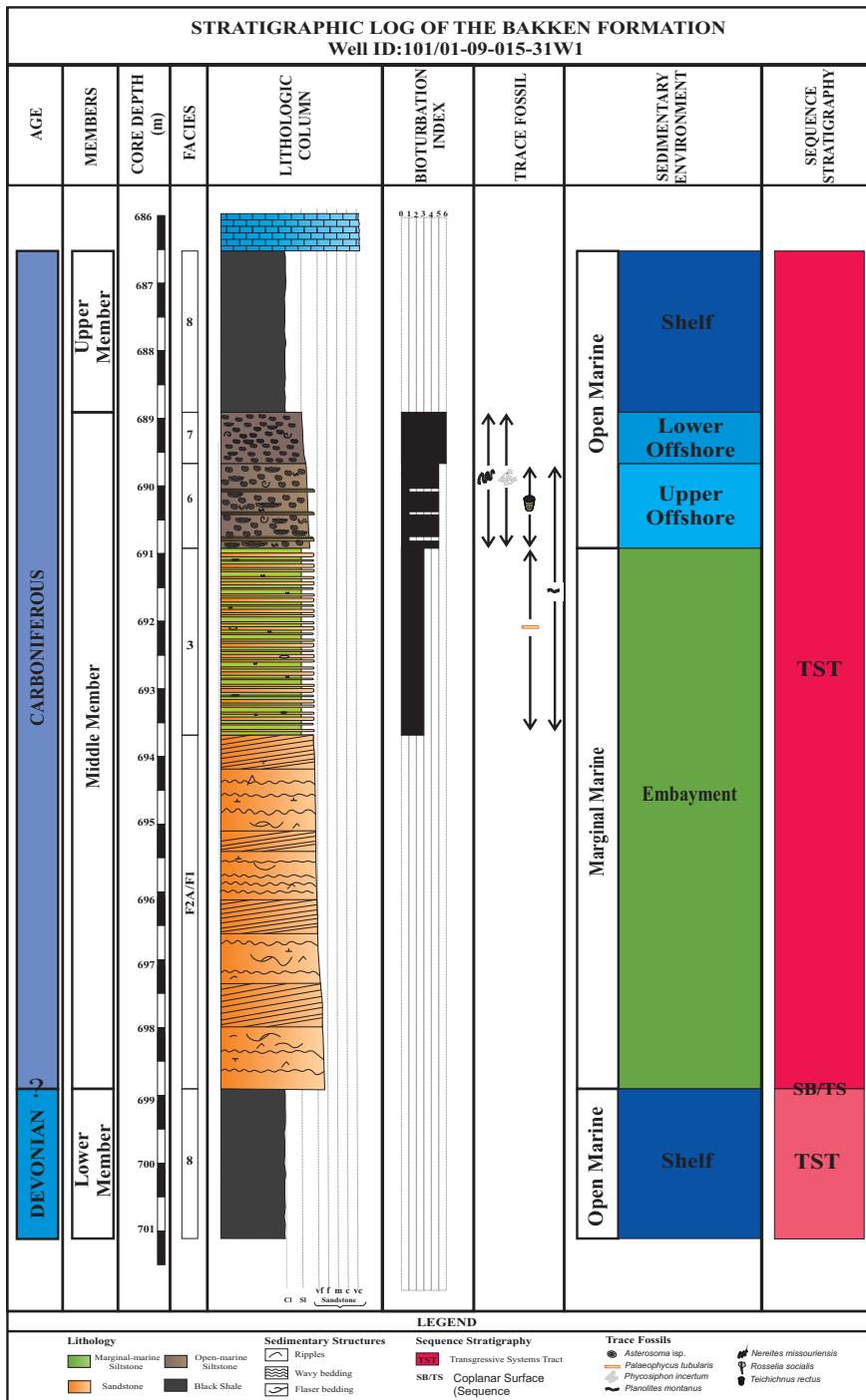
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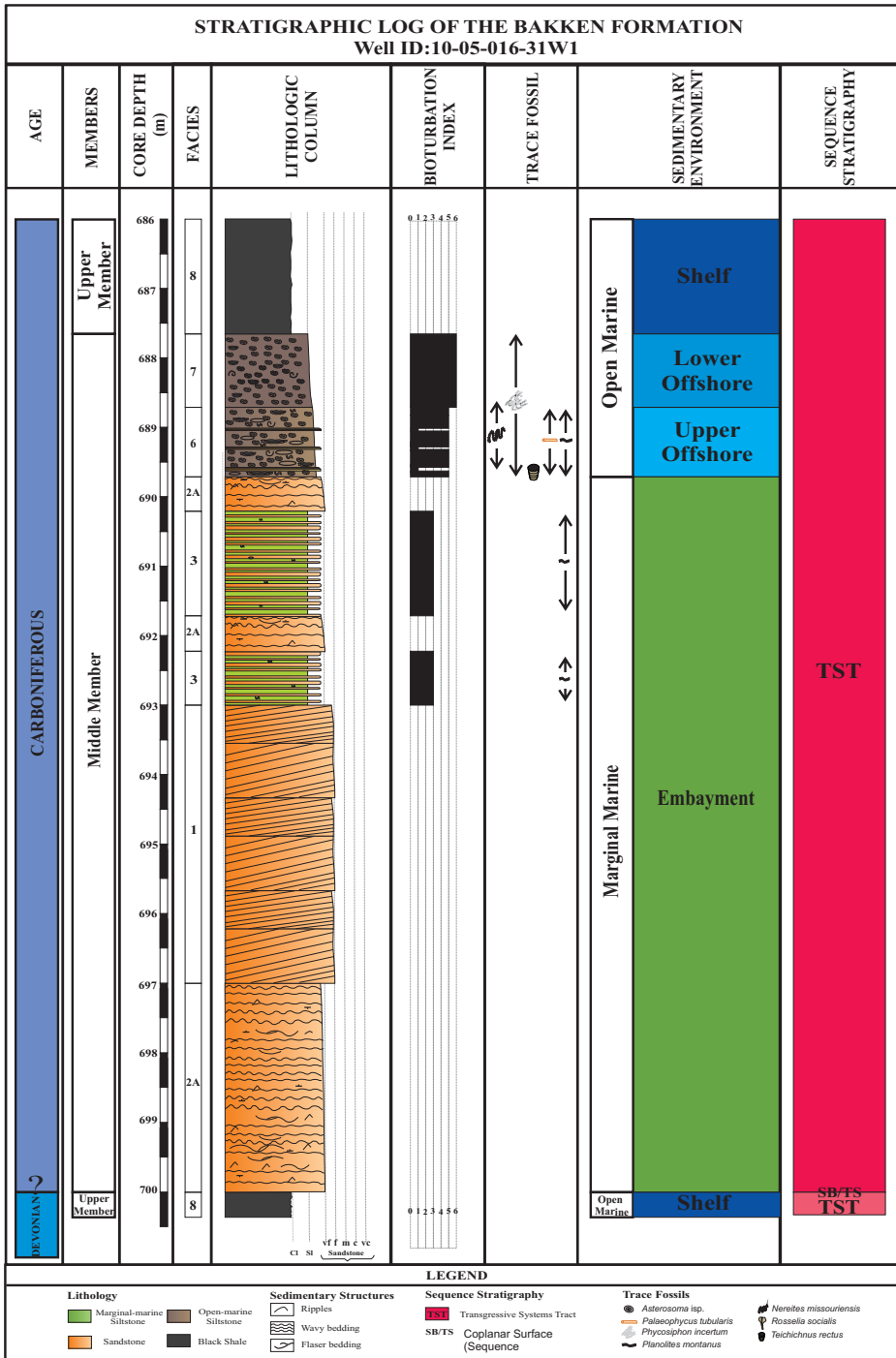


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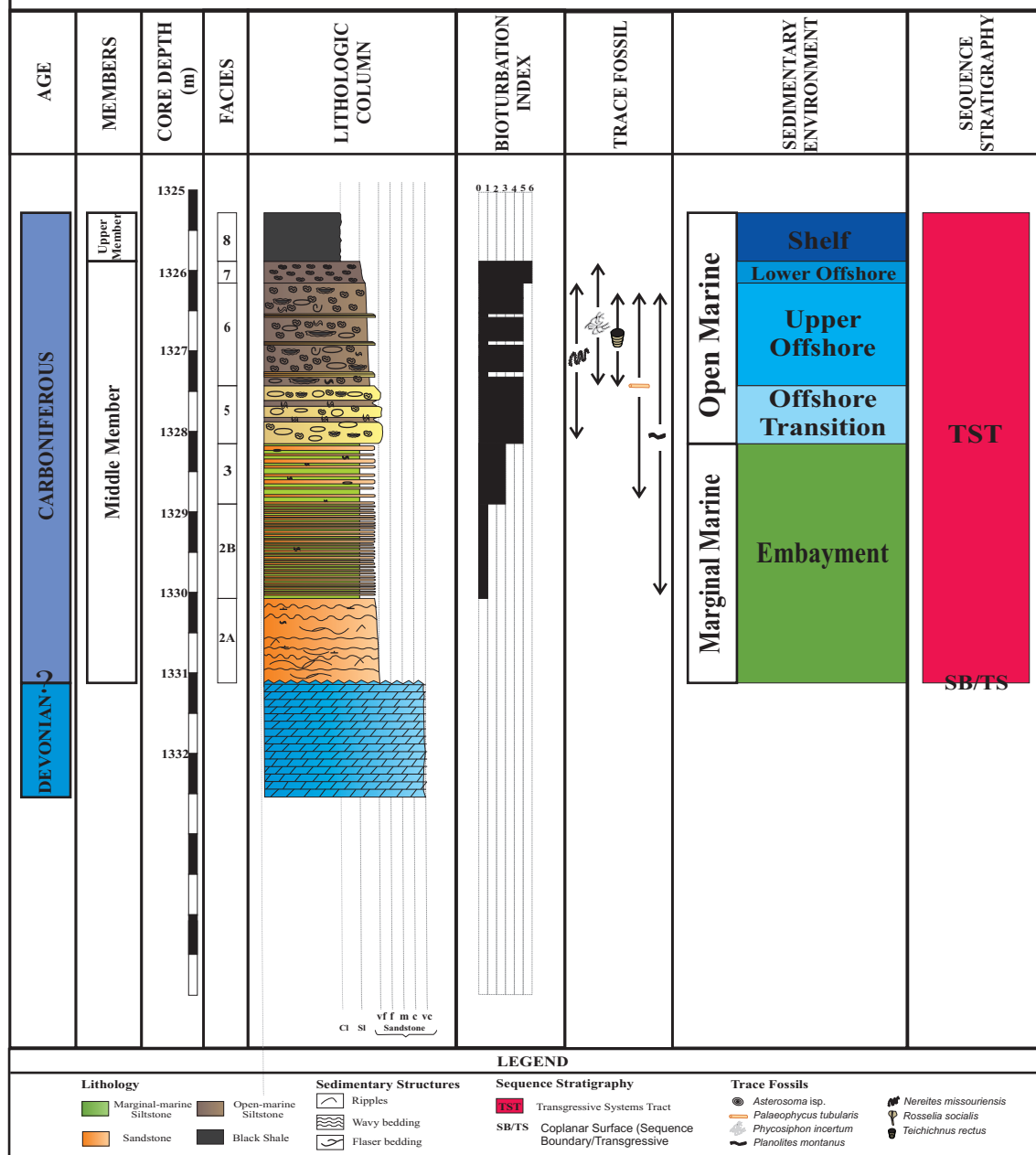






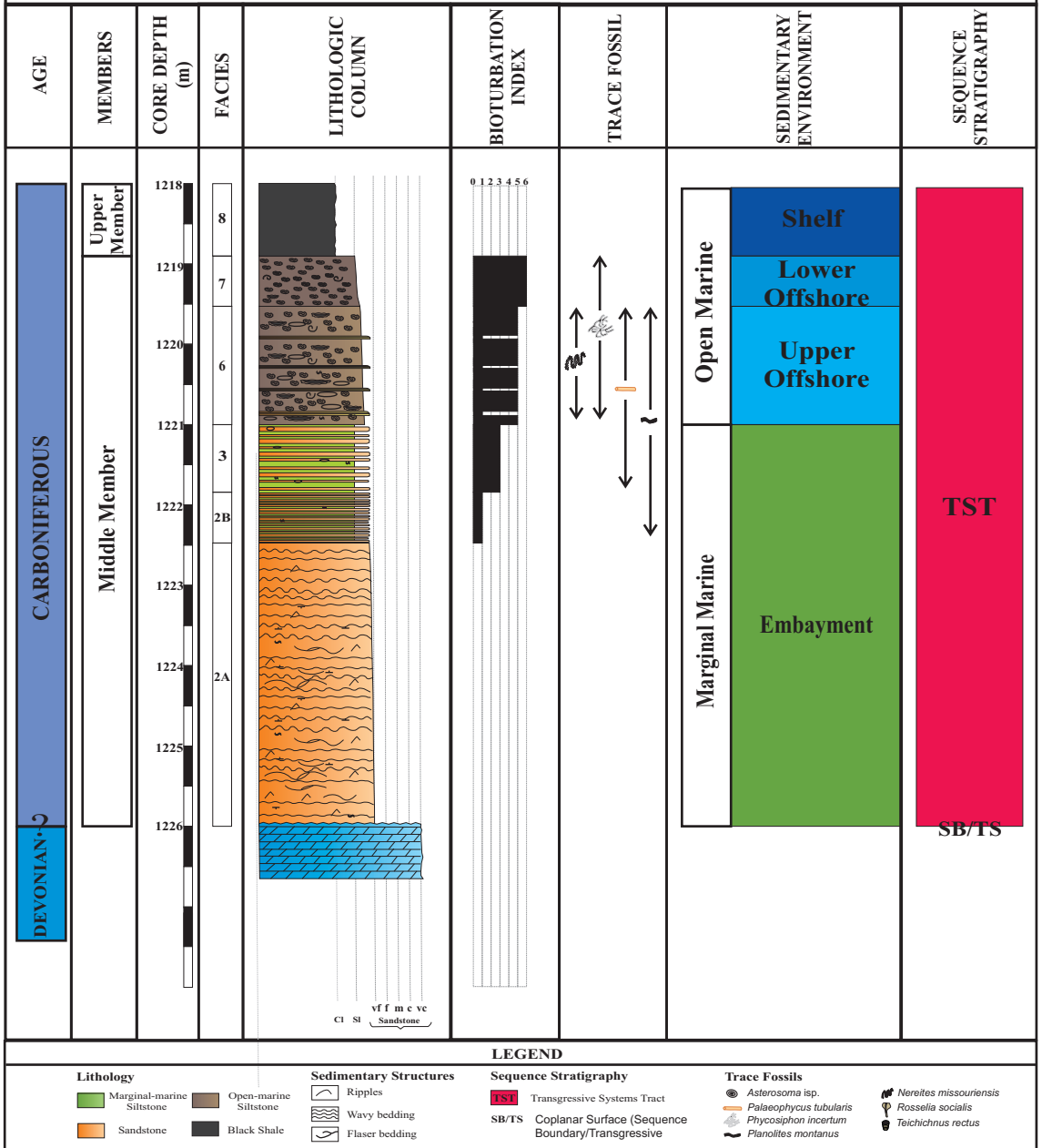
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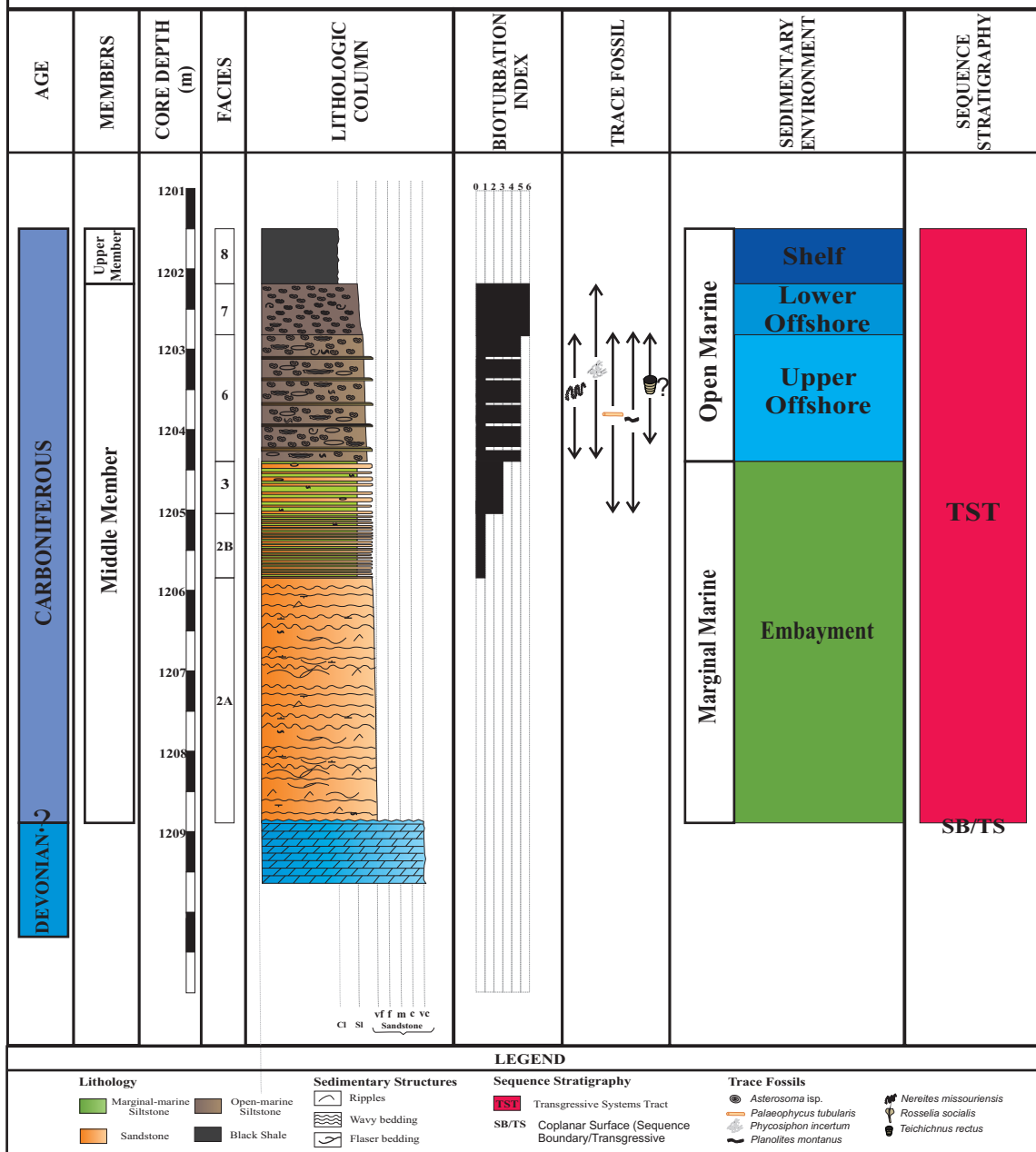
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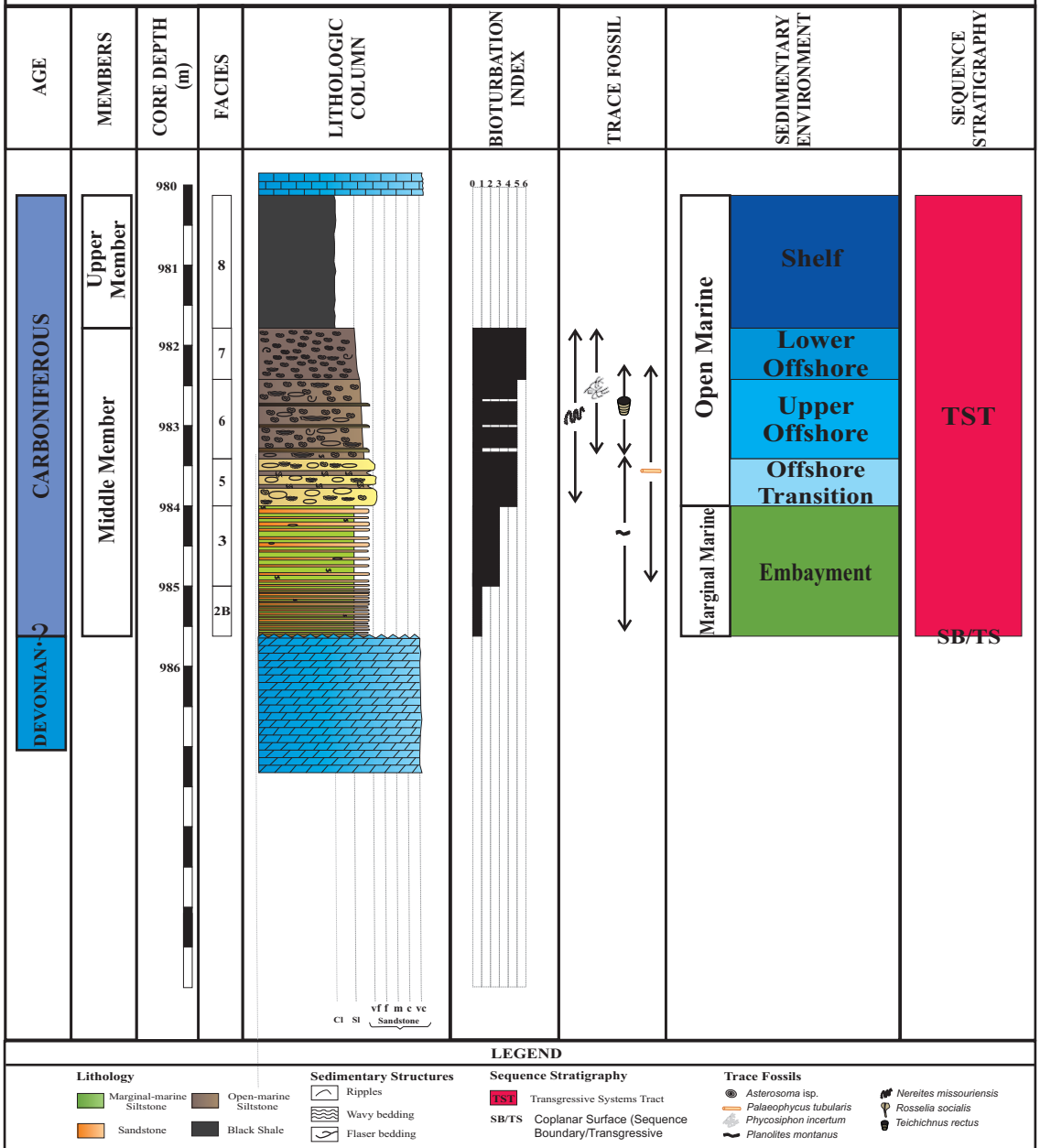


STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

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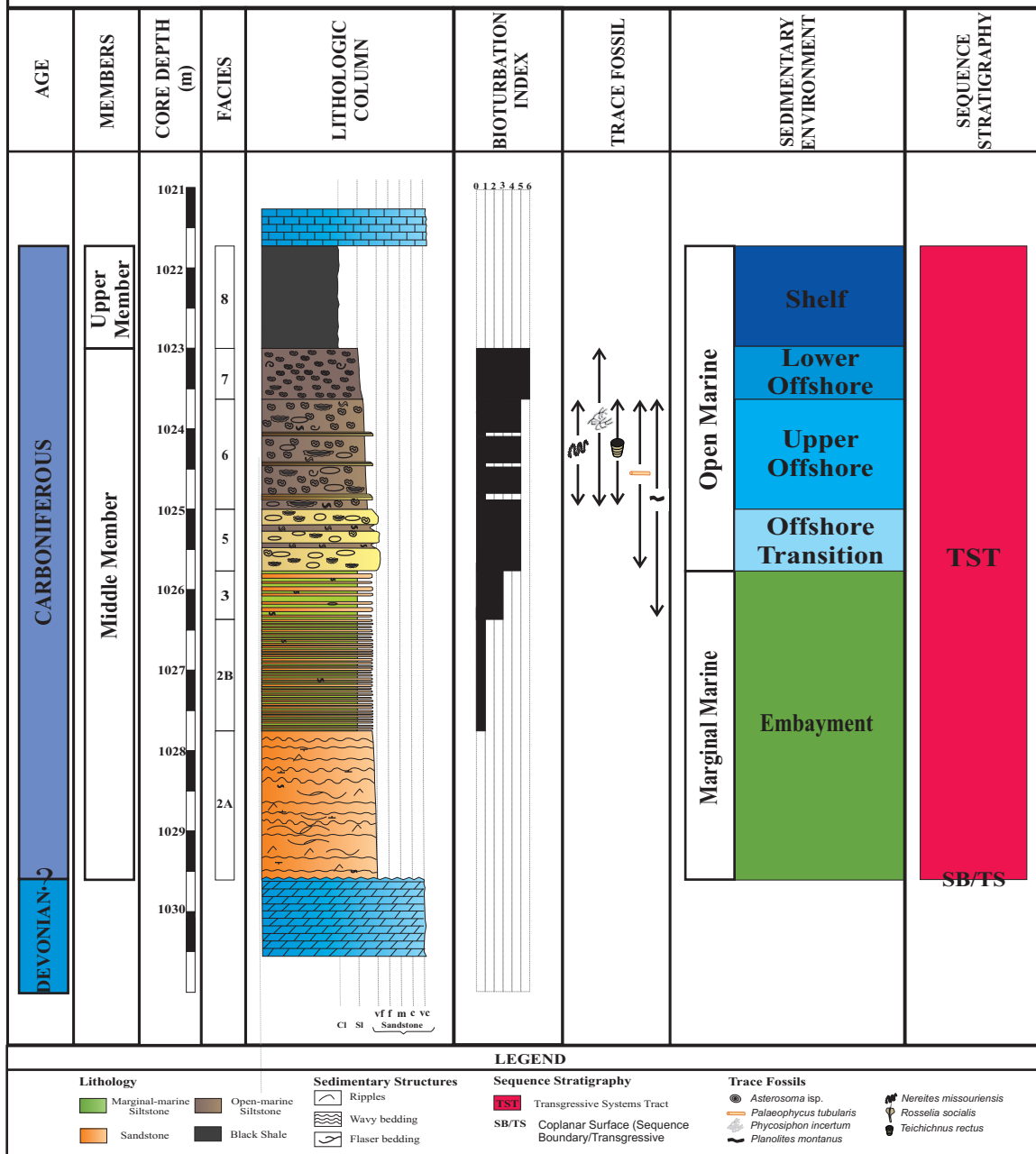


STRATIGRAPHIC LOG OF THE BAKKEN FORMATION
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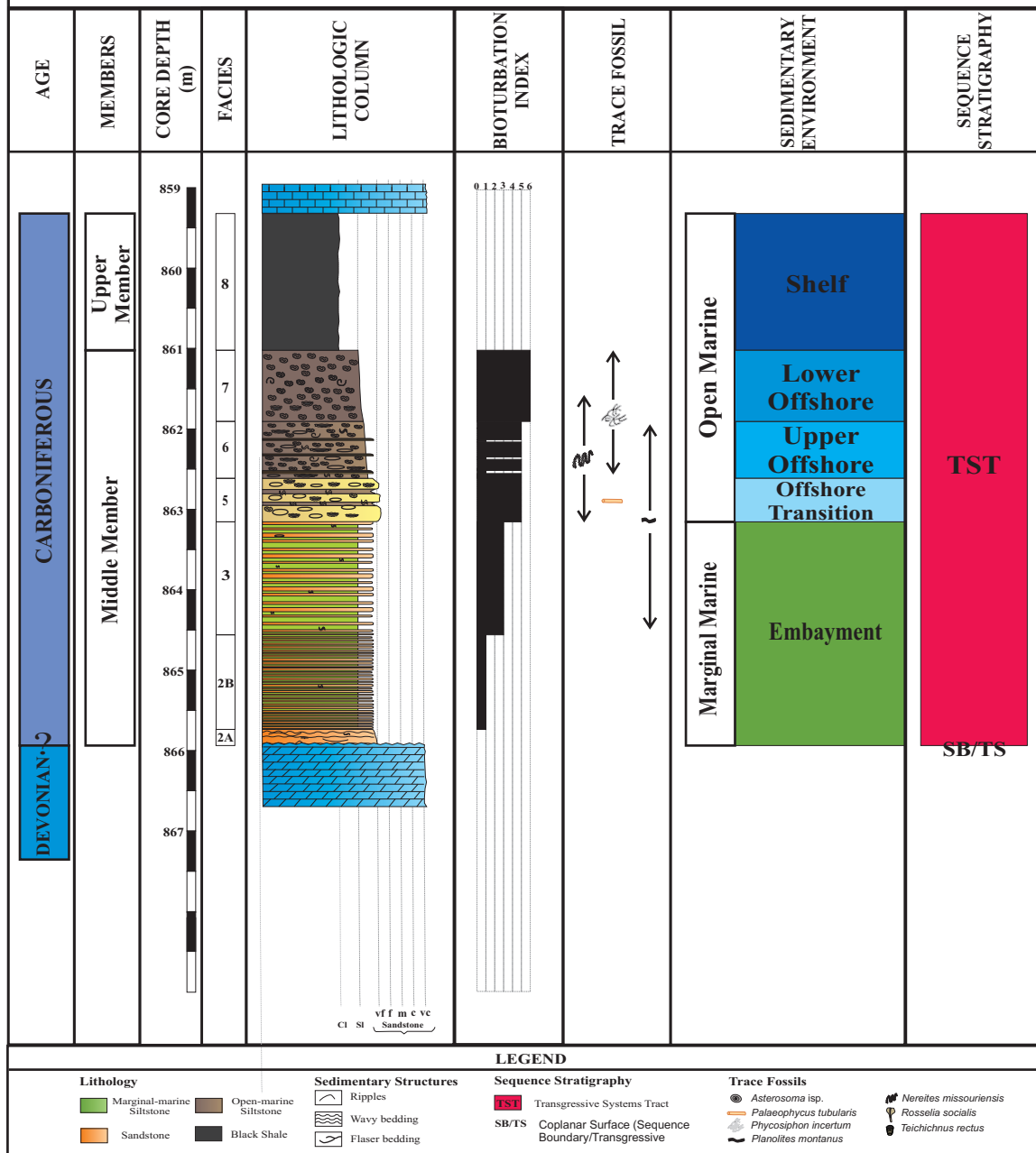
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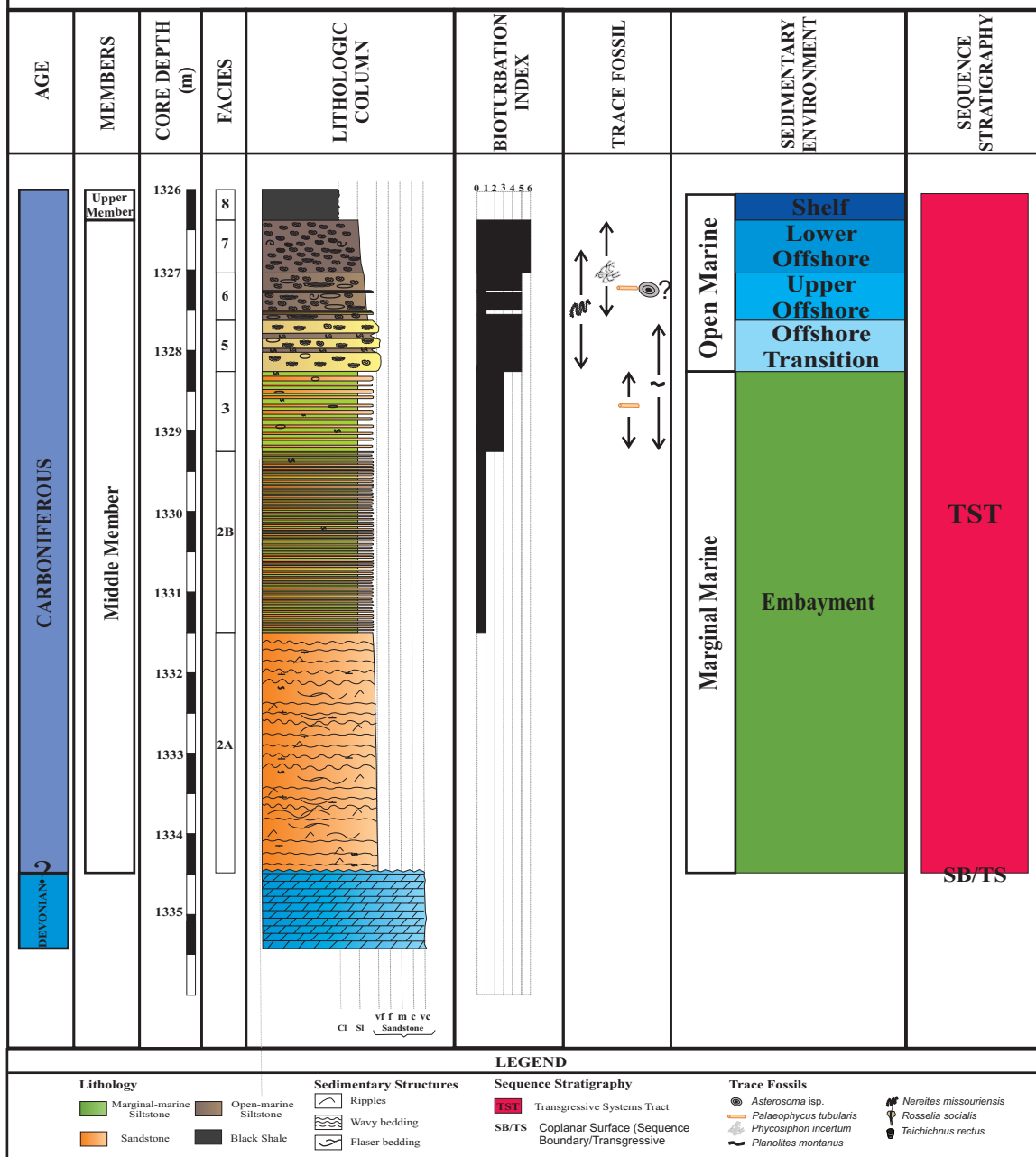
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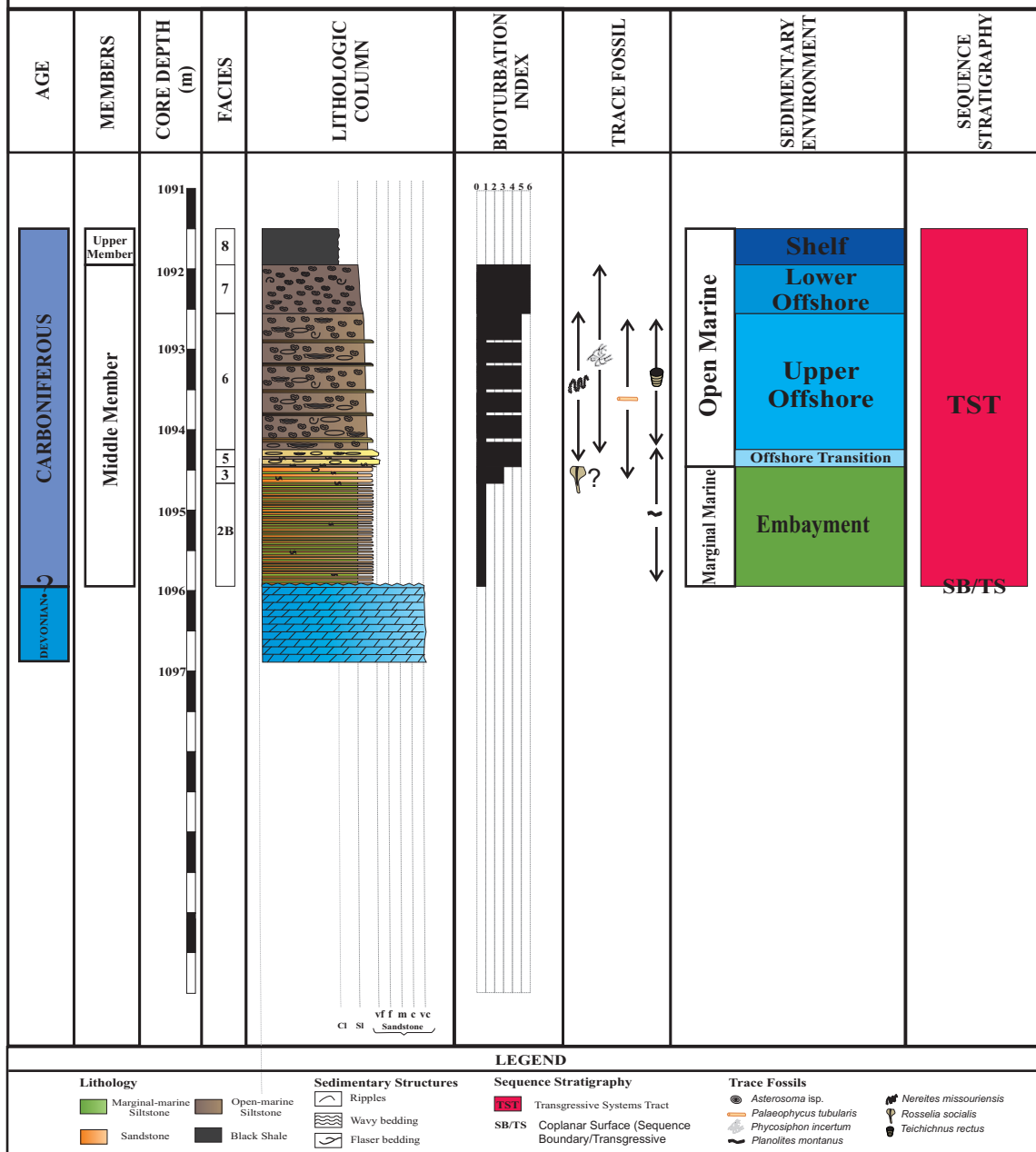
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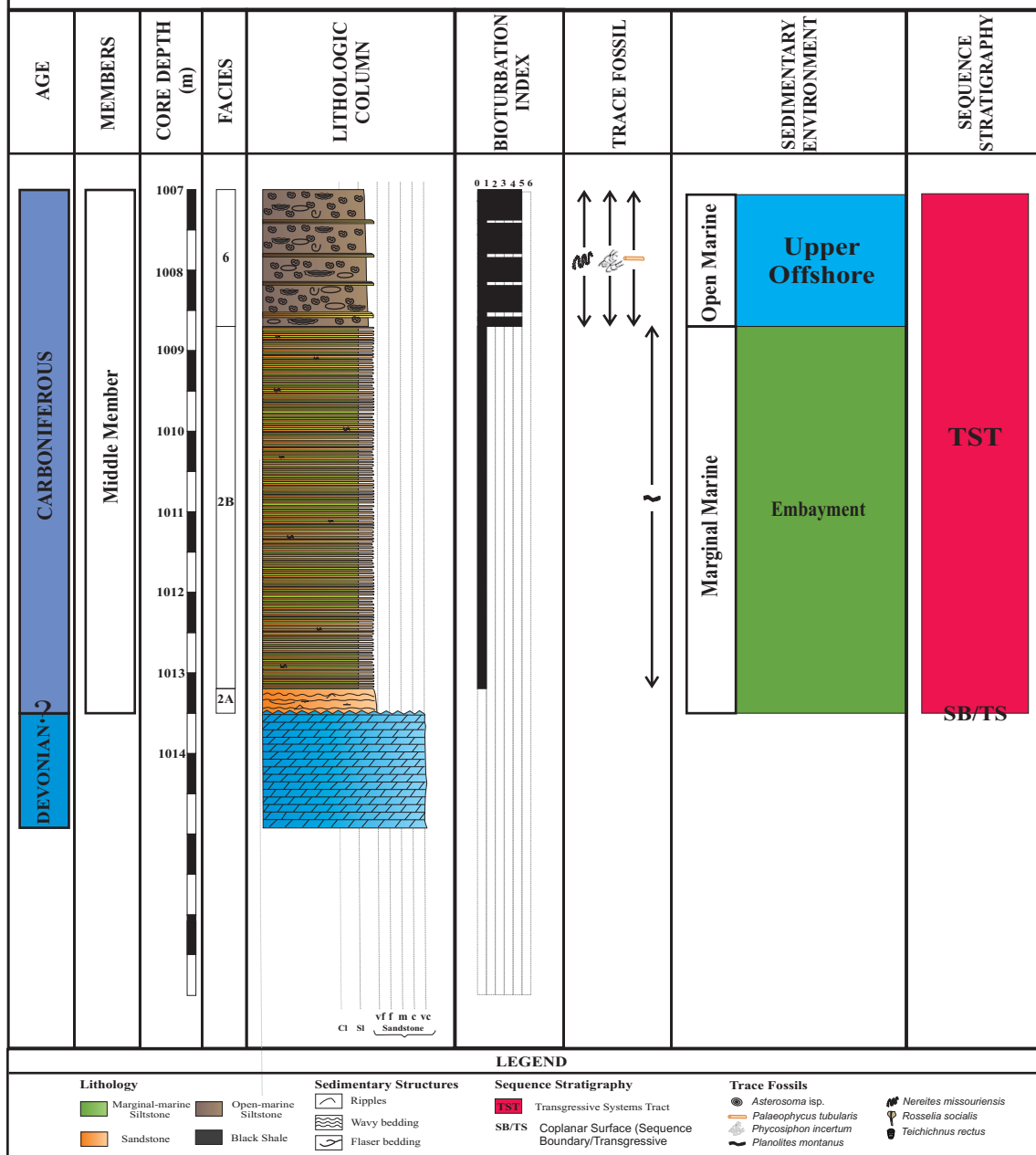
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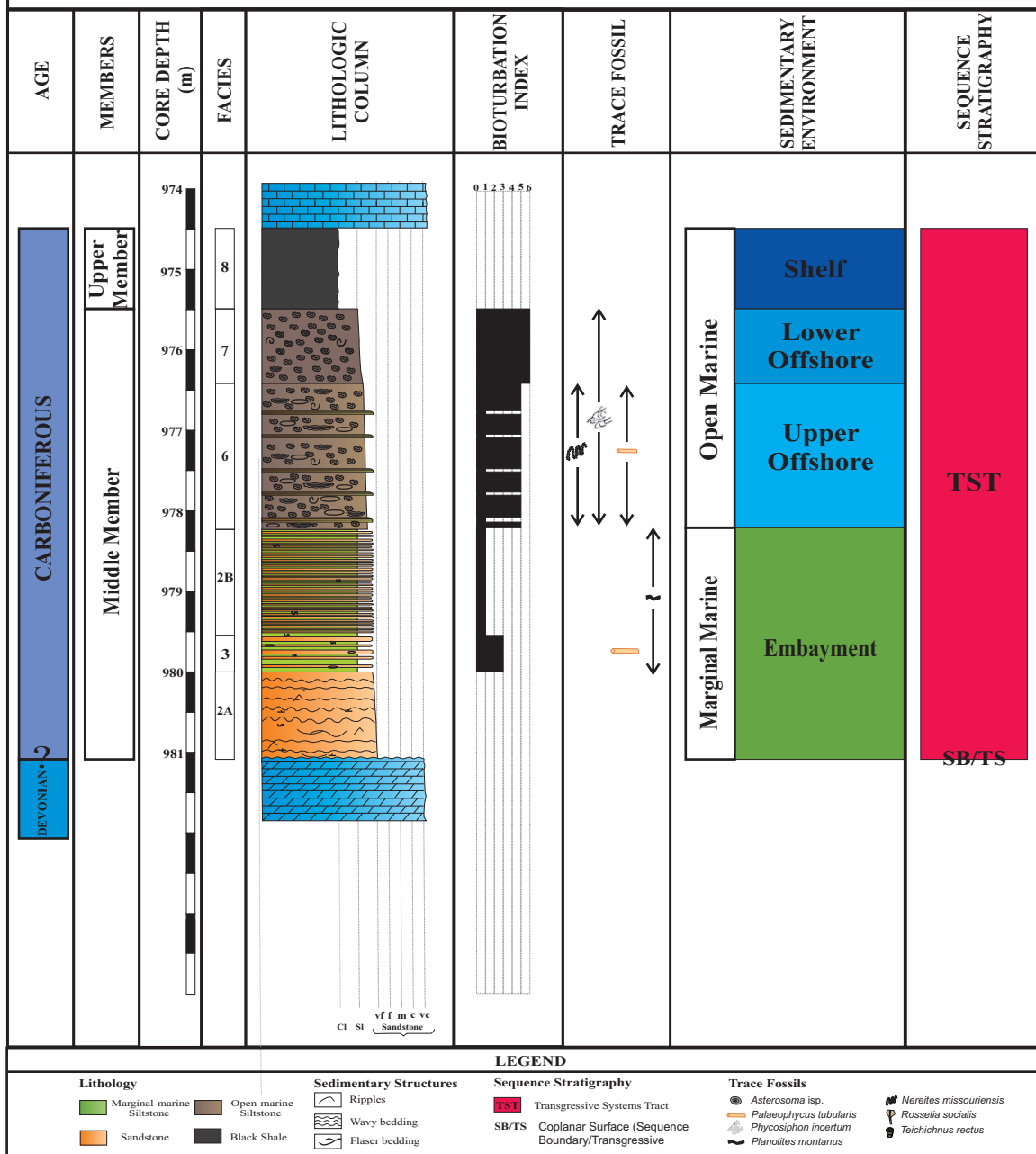
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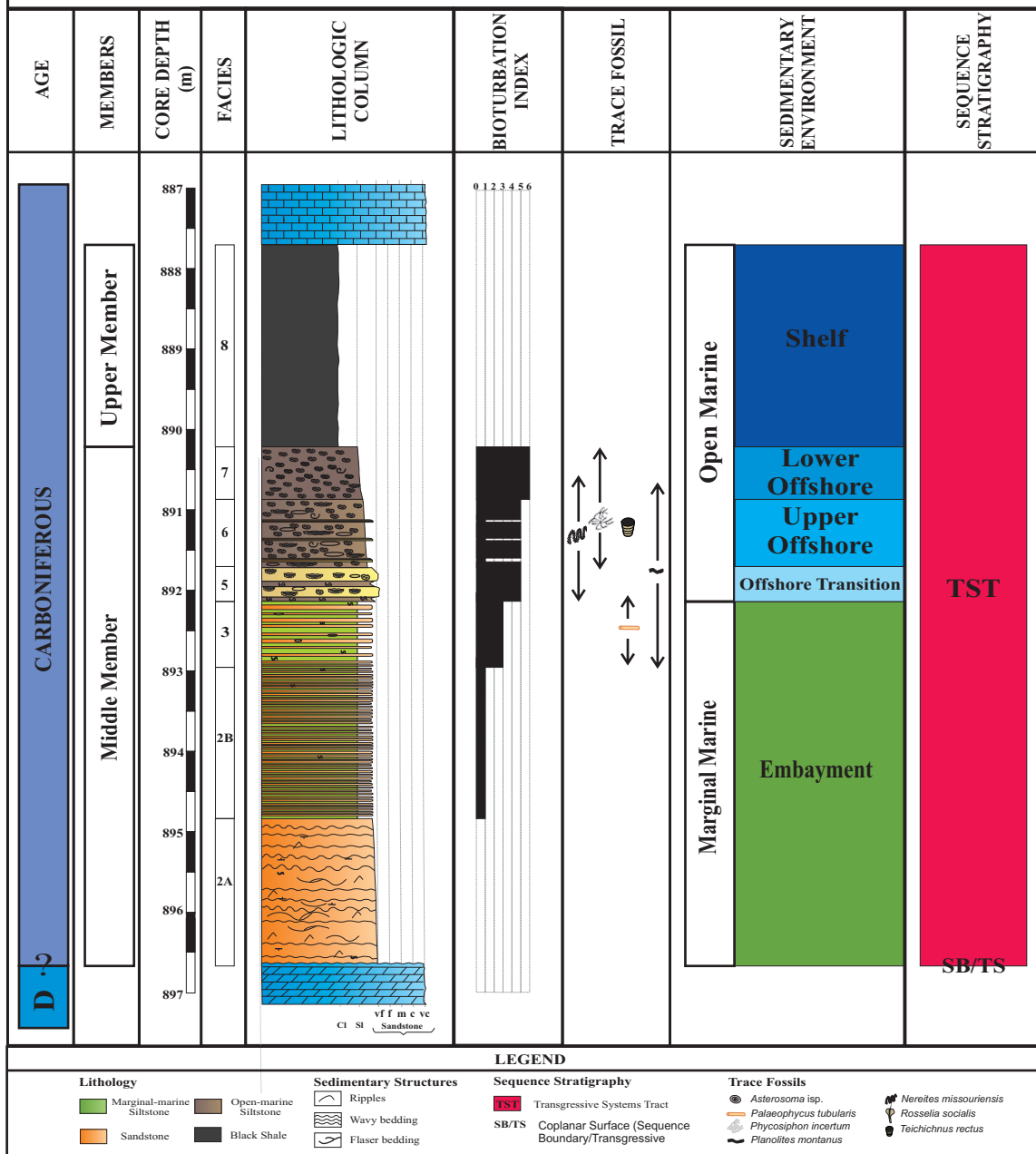
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Well ID:131/13-27-012-33W1



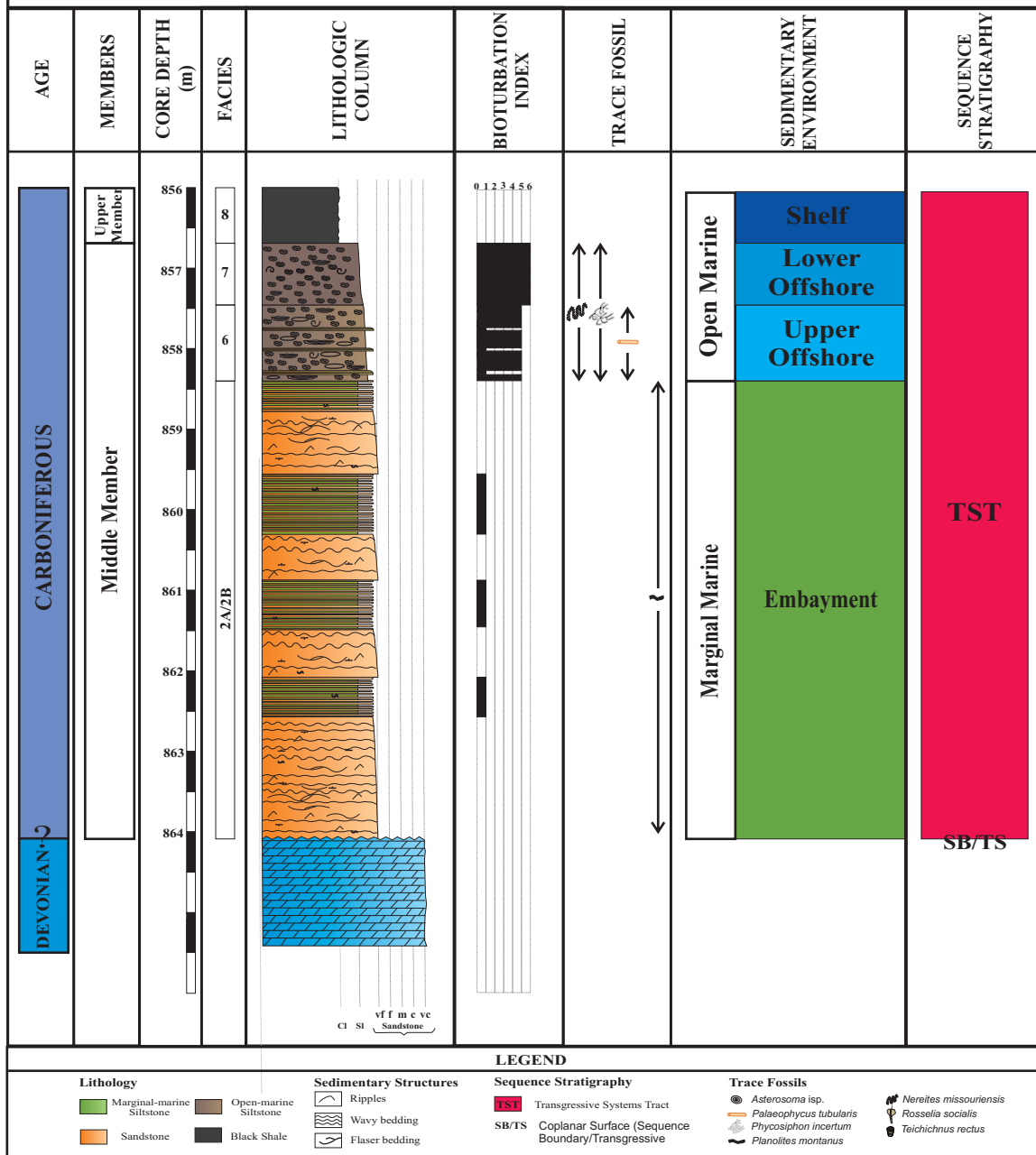
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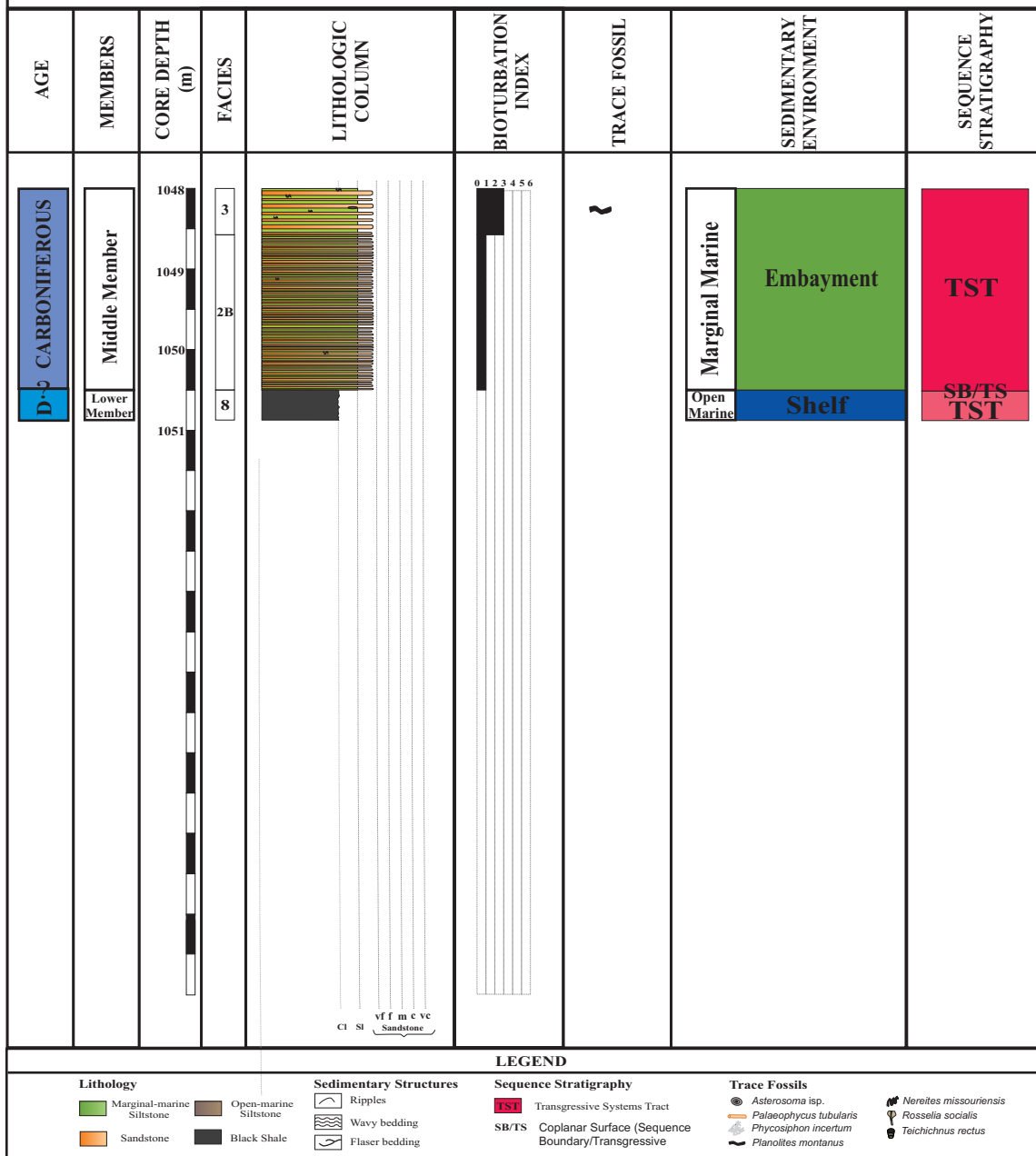


STRATIGRAPHIC LOG OF THE BAKKEN FORMATION

Well ID:102/09-22-014-33W1



STRATIGRAPHIC LOG OF THE BAKKEN FORMATION Well ID:141/11-25-012-01W2



STRATIGRAPHIC LOG OF THE BAKKEN FORMATION **Well ID:131/16-24-013-02W2**

